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BY
ANJA THRANE HEJSELBÆK THOMSEN

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LIST OF SCIENTIFIC PAPERS

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ENGLISH SUMMARY

A focus point in today's stormwater management is the effects of stormwater discharge from urban areas to the receiving water bodies, and thus how stormwater can be managed in the most efficient and environmentally sustainable way. Despite this, however, there is no consensus on how requirements should be set in relation to stormwater discharges. The practice in several countries is to establish stormwater detentions ponds, which are designed to accommodate the local requirements for the maximum discharged flow rate. The reason for establishing such requirements is that discharges of too-high flow rates will potentially have a negative effect on the receiving steams, for instance by causing flooding or erosion. There are several ways to ensure that the permitted discharge flow rate is not exceeded, but most often this is solved by implementing passive flow regulation devices such as water brakes, throttling pipes or sliding valves.

Even though many resources are used by the authorities to determine the maximum allowed discharge for the discharge permit, monitoring and documenting the discharge is rarely a requirement. However, monitoring makes it possible to document both the discharge flow rate and the number of overflow events, which is important knowledge for both the authorities in the municipalities and the water utility companies. A side-effect of monitoring is that we gain an improved level of knowledge about the effect of different regulation devices, how the discharge affects the receiving stream, and how the flow rate specified in the discharge permit affects pond efficiency and thus the detention period, pond filling and how much time it takes to empty the pond.

In order to improve the possibilities of monitoring the discharge from stormwater detention ponds, this project has developed a cost-effective and simple method for monitoring discharges from all types of flow-regulated stormwater detention ponds, regardless of regulation device. This method relies on measurements from a permanent water level gauge in the detention pond. Based on the water level monitored for the duration of emptying the pond after a rain event, the changes in water level can be converted to a discharged flow rate based on detailed knowledge of the pond geometry. If such analyses are performed for multiple rain events, a rating curve can be established. This rating curve will describe the relation between water level and discharge. Thus, after establishing the rating curve, a measured water level can simply be converted to a discharged flow rate, and the water level gauge also works as a discharge flow gauge.

In order to quantify the effects of discharges from stormwater detention ponds into streams, full-scale experiments have been conducted in a stream which receives water from a detention pond. The experiments aimed to determine whether a relation between discharge and sediment transport could be established. The first experiment

focused on establishing this relation and defining the threshold of increased sediment transport. This was done by a step-wise increase of the discharged flow. Throughout this experiment, the sediment transport in the stream was measured continuously. The studies showed that there was a non-linear relation between sediment transport and discharge. In order to generalise the result of this study, 11 methods for calculating critical shear stress and critical stream power were tested and compared to the measured results. It turned out that none of the methods tested were able to predict critical conditions for sediment transport. It is expected that the reason for this is the form roughness of the stream. Due to the energy loss within the stream, only a limited part of the potential energy in the water is converted to sediment transport. Likewise, the availability of sediment may interfere with the results.

A second experiment was conducted to determine the variation in sediment transport within the stream. The results from this experiment showed a significant local variation in sediment transport. The highest level of sediment transport occurred approximately 700 meters downstream from the discharge point. Usually, this would be expected around the discharge point.

Based on the results from these experiments, it was possible to determine the critical conditions for sediment transport. Likewise, it was possible to determine the stream flow which would lead to flooding based on simulations in a dynamic stream model (MIKE 11). Thus, the stream capacity could be defined as the highest flow not resulting in any of the aforementioned critical conditions. Based on this flow, five different control strategies were tested in order to determine which was the best for balancing the impacts on the stream while still ensuring efficient stormwater management. It turned out that it was not possible to give a clear answer based on the results from this experimental site. However, a predictive control strategy had the overall best performance minimising the negative effects in the stream without requiring a larger detention pond. These results showed that one way to ensure that the capacity of streams is actively considered could be by implementing control structures and creating a control strategy specifically constructed for the individual system. However, this requires detailed knowledge of the dynamics of the stream.

DANSK RESUME

Der er i dag et stort fokus på effekter af regnvandsudledninger fra urbane områder til recipienter og på, hvordan regnvand skal håndteres mest effektivt, hensigtsmæssigt og miljøskånsomt. Dette til trods er der dog ingen konsensus om, hvordan der skal stilles krav i forhold til udledninger af regnvand, men praksis i flere lande er, at der etableres regnvandsbassiner med krav om en maksimalt acceptabel udledningsstørrelse. Årsagen til dette krav er, at uforsinkede og kraftige udledninger har en negativ effekt på vandløbene – eksempelvis i form af oversvømmelse og erosion. Der er flere måder at sikre, at den tilladte udledningsstørrelse ikke overskrides, men oftest anvendes passivt udløbsregulering så som vandbremser, droslerør og spjæld.

Til trods for at myndighederne bruger mange ressourcer på at fastlægge den maksimalt tilladte udledning, som danner grundlag for udledningstilladelsen, stilles der sjældent krav om monitering af udledningen, der gør det muligt at dokumentere, at udledningstilladelsen overholdes. Der er dog en stor interesse hos både kommuner og forsyningsselskaber i at monitere udledningen fra, og tilbageholdelsen i, bassinerne, eftersom det derved er muligt både at dokumentere størrelsen af udledningen og frekvensen af nødoverløb. Herved vil der ligeledes kunne oparbejdes en viden om droslingseffekten af forskellige reguleringsbygværker, påvirkning af det modtagende vandområde, og hvordan udledningsstørrelsen påvirker bassinets effektivitet (fyldningsgrad og tilbageholdelsesperiode).

For at forbedre mulighederne for at monitere udledningen fra regnvandsbassiner er der gennem dette projekt udviklet en omkostningseffektiv og simpel målemetode til monitering af udledninger fra alle typer udledningsregulerede regnvandsbassiner – uanset hvilken reguleringsmekanisme, der er anvendt. Metoden bygger på installationen af en vandstandsmålestation. Gennem målinger af vandstands-ændringerne i forbindelse med en regnhændelse kan man med udgangspunkt i et detaljeret kendskab til bassinets geometri konvertere vandstandsændringerne til en udledningsstørrelse. Såfremt sådanne analyser udføres i forbindelse med flere regnhændelser, kan der etableres en Qh-kurve, som beskriver sammenhængen mellem vandstand og udledning. Herefter kan vandstanden på simpel vis konverteres til en udledningsstørrelse, og bassinets udledning kan beregnes og overvåges fremadrettet.

For at undersøge effekterne af udledninger i vandløbene er der gennem dette studie lavet fuldskalaforsøg i et vandløb, der modtager udledninger fra et regnvandsbassin. Forsøgene havde til formål at bestemme sammenhængen mellem udledning og sedimenttransport på en forsøgslokalitet. Først blev der udført et forsøg, hvor udledningen fra bassinet trinvist blev øget. Gennem dette forsøg blev sedimenttransporten i vandløbet kontinuerligt målt, hvorved en tærskelværdi for sedimenttransport kunne fastsættes. Undersøgelserne viste, at der var en ikke-lineær sammenhæng mellem sedimenttransport og udledning. For at kunne generalisere resultatet af denne undersøgelse blev 11 metoder til beregning af hhv. kritisk bundforskydnings-spænding og kritisk stream power afprøvet og sammenlignet med de målte værdier fra forsøgene. Det viste sig, at ingen af de afprøvede metoder kunne anvendes til at forudsige kritiske forhold for sedimenttransport i vandløbet. Dette skyldes formodentlig vandløbets formrughed, der medfører, at kun en mindre del af den potentielle energi i vandet omsættes til sedimenttransport. Ligeledes kan tilgængeligheden af sediment spille en rolle. Forsøgene viste, at der var en signifikant lokal variation i sedimenttransporten ned igennem vandløbet, og at den største sedimenttransport skete ca. 700 meter nedstrøms udledningspunktet. Normalt ville man forvente, at dette opstod omkring udledningspunktet.

På baggrund af målingerne var det muligt at fastsætte de kritiske forhold i relation til sedimenttransport. Og ud fra beregninger i en dynamisk vandløbsmodel (MIKE 11) blev det beregnet, hvornår der ville forekomme oversvømmelser i vandløbet. Den vandføring, der netop ikke gav anledning til nogen af førnævnte kritiske forhold, blev brugt til at definere vandløbets kapacitet. Med udgangspunkt i denne vandføring blev fem styringsstrategier testet for at vurdere, hvilken der bedst balancerer hensynet til recipienten og sikring af en effektiv vandhåndtering. Det viste sig, at det ikke var muligt at uddrage en tydelig konklusion for netop denne lokalitet. Men en aktiv prædiktiv styring havde den overordnet bedste effekt i forhold til at imødekomme kravene og minimere de negative effekter i vandløbet uden at det er nødvendigt at etablere ekstra tilbageholdelsesvolumen i bassinet. Disse resultater viste, at en måde, hvorved det kan sikres, at vandløbenes kapacitet aktivt tages i betragtning, kunne være at implementere styring. Dette kræver dog et detaljeret kendskab til vandløbets dynamik.

PREFACE

This research project is an industrial Ph.D project carried out in a cooperation between the consulting engineering company Orbicon|WSP and Aalborg University. The study is funded by the Innovation Fund Denmark and Hedeselskabets Innovationsfond (the Innovation Fund of Hedeselskabet). Furthermore, three municipalities and water utility companies (Vejle Kommune and Vejle Spildevand A/S, Aarhus Kommune and Aarhus Vand A/S, and Randers Kommune and Vandmiljø Randers A/S) have supported the project by providing experimental locations and by financing the permanent measurement equipment at the four test sites.

The project takes as its point of departure that the lack of knowledge about the effect of urban discharging to streams has significant consequences for the design practices of stormwater detention ponds. If it is not possible to estimate the consequences of a particular discharged flow rate, the authorities have to issue highly restrictive discharge permits, which often causes larger (and thus more expensive) detention ponds than necessary. The reasoning behind this project is that it is of national interest to make investments in water utility companies according to costs and effects. If we aim for the most environmentally beneficial investment possible, this will not come from making large investments in a few expensive and possibly oversized detention ponds – it will come from making detention ponds which are just the right size.

A priority should also be to monitor the *existing* discharge, both in order to quantify the actual discharge and its current impact. Furthermore, it is necessary to be able to calculate the capacity of a stream in order to determine the maximum discharged flow rate which should be permitted based on its effects – or else it is necessary to make the conservative and more expensive investment. The task of determining the correct maximum discharge from detention ponds is important for both the local authorities and city planners in the municipalities, and for the executive planners and investment planners in the water utility companies. This is the reason why the project was done in cooperation with both the municipalities and water utility companies – to ensure that most of the crucial aspects were taken into account.

One of the criteria of Hedeselskabets Innovationsfond for supporting the project financially was that the knowledge generated through the project should be shared publicly with stakeholders within the field of discharge analysis. Because of this, the project has been followed by over 30 pairs of municipalities and water utility companies in the last 3.5 years, through six workshops with approximately 70-90 participants. Here, the latest research results were presented along with new and innovative projects from either Orbicon|WSP or the participating municipalities and water utility companies. Additionally, expert knowledge from specialists within law or from universities was presented. This resulted in many interesting discussions and some corrections of the project in order to comply with the issues experienced by the stakeholders. Pictures from stakeholder workshops will be shown below.

One of the primary results of the workshops was that if an active control strategy for stormwater detention ponds requires a connection to the main public power supply and maybe the Internet, this might cancel out the savings gained by establishing smaller detention ponds. In order to get the benefits of control, the system has to be economically sustainable.

Thus, we started a collaboration with a producer of a flow regulation devices (Mosbaek A/S) in order to produce an agile low-energy water brake which runs on batteries or solar energy. This will make it possible to achieve the savings in establishing costs from optimising the utilisation of the detention ponds by controlling the discharge. The project is supported by VUDP (Programme for Development and Demonstration of Technology in the Danish Water Sector). Furthermore, the project is carried out in collaboration between Mosbaek A/S, Aalborg University, Orbicon|WSP and Favrskov Forsyning, a water utility company.

Pictures from two of the workshops with the stakeholder committee

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To my supervisors, Michael, Gunnar and Bjarne (and Jesper – you may not be my supervisor on paper, but in reality, you were, and you were a great one!), thank you for all your input and contributions during the project.

Being at the university is always inspiring, primarily due to the people I always meet. So, thank you to all of my roommates and “neighbours” for bringing happiness and joy in the most stressful days; Kristoffer, Rasmus, Christoffer, Lasse, Amelia, Niels, Jes, Michael, Søren and Jesper. It was a joy to share the office with you, and I promise to bring some sweet and heavy cake if you will let me join you at the office once in a while in the future. A special thanks to Anette for helping me in the laboratory, and to Henrik for both the remote support at the most inconvenient times, and for going with me to Vejle on several occasions – the sliding valve would not have worked had it not been for you. I would also like to say a special thanks to my fellow industrial Ph.D student Kristoffer for your moral support and for a constructive conversation about both academic subjects and balancing the stakeholders in the project.

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I would also like to express my gratitude to my collaborators in Randers, Aarhus and Vejle. I truly appreciate that you joined the project and let us work at the four experimental sites, were available for all my questions, and furthermore that you supplied us with the monitoring equipment which allowed us to obtain deeper knowledge about the dynamics in the systems. A special thank to Vejle and my primary collaborators Paul and Claus for letting me use “my” pond and Polsterbæk as a playground for all the interesting experiments with sediment transport, and for installing the sliding valve in such a way that it was possible for me to control the discharge.

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CHAPTER 1. INTRODUCTION

Streams and rivers are the primary water connections between inland areas and the sea. Therefore, streams receive water from a number of man-made sources, such as drainage systems, discharge from factories (process water), runoff from unpaved areas, urban discharges from wastewater treatment plants, combined sewer overflow, discharge from separate stormwater detention ponds, etc. (e.g. Phillips and Chalmers, 2009). Furthermore, many streams have historically been regulated, for example by being expanded, deepened and straightened in order to improve their drainage efficiency. In many cases, these changes in the stream morphology have been made at the expense of the stream's ecological quality (Bunn and Arthington, 2002). However, at present, the focus has changed towards creating good hydrological and ecological conditions in the streams. This work is supported and initiated by, among others, the European Water Framework directive (European Commission, 2000). Here, the focus is on the goal of ensuring good ecological conditions in the stream, which makes it necessary to reconsider the way in which many of the sources which discharge to the streams are managed.

On the other hand, urban stormwater management is challenged by climate changes which result in more intense rain events, and thus, the capacity of the systems is exceeded more frequently, resulting in emergency overflow events. The European Environment Agency (2019) predicts that the heavy rain events experienced in Europe will generally increase by 15-35% during the winter season and 5-25% during the summer season.

Thus, an important task for water utility companies and local environmental authorities is to protect the receiving water bodies from the potentially harmful effects of urban discharges. Traditionally in developed countries, stormwater is led in an underground sewer system, which is either a combined sewer system, which leads both stormwater and sewage to the wastewater treatment plant, or a separate sewer system, which leads the sewage to the wastewater treatment plant and discharging the stormwater to the nearest body of water (e.g. Tyson, 2004). Due to the health risks and acute pollution in the receiving water bodies during emergency overflows from combined sewer systems, the separate sewer system is currently the preferred system.

Since the 1970's, stormwater detention ponds have been a widely accepted tool to detain runoff from urban areas (Guo, 2007); thus, stormflow is not discharged directly into the stream. Now, stormwater detention ponds are one of the most common stormwater handling methods in many countries (Tixier et al., 2011). The reason why it often is necessary to have detention ponds as a buffer between the urban stormwater system and the receiving water bodies (primarily streams) is the need to reduce the peak runoff from urban areas. Increased urbanisation has resulted in more impervious areas, and thus and faster runoff. This, combined with an efficient subsurface storm drainage network, increases the storm runoff peak during large rain events (Price, 2011, and Walsh et al., 2005b). The primary role of the stormwater drainage system is to transport the stormwater fast and efficiently away from the urban areas and important infrastructure. Therefore, discharge from urban areas often results in a decreased time to peak compared to the natural hydrological process of runoff (Cheng and Wang, 2002). The effect on both the time to peak and size of the peak during the discharge depends on both the catchment characteristics, such as slope and size, and the urbanisation percentage of the catchment (Rose and Peters, 2001).

If the discharge from the urban stormwater drainage system is not regulated or the allowed discharged flow rate from the detention pond is too high, this will potentially damage the stream ecosystem as well as flooding infrastructure, buildings and the agriculture along the path of the stream. Some of the observed negative effects of stormwater discharges are increased flooding, which may be both more frequent and widespread, increased erosion of both the stream bed and the stream banks, decreased groundwater table, and increased pollution of the streams (Hatt et al., 2004). All those processes can, together or individually, negatively affect the aquatic ecosystem in the streams (Paul and Meyer, 2001; Walsh et al., 2005a; Booth and Jackson, 1997; and Walsh, 2000).

The primarily concern regarding too-high discharged flow rates are flooding and erosion, since these parameters are highly dependent on the resulting stream flow and thus the amount of discharge. According to e.g. Sand-Jensen (1998), Joiner et al. (2014) and Aulenbach et al. (2017), erosion often occurs in streams experiencing a high hydraulic load, due to the correlation between velocity (and thus also shear stress) and erosion. When the resulting flows in the streams are too high, this might exceed the natural variation of the velocity (and shear stress), which could potentially result in excessive erosion affecting the stream habitat and stability. This often makes it difficult to meet the requirements of the European Water Framework Directive (Brils, 2010). The reason for this is that erosion has an impact on the physical parameters of the stream, and the ecological status in a stream is highly dependent on the quality of the physical habitat and the hydraulic loads (Poff et al., 2010; Poff et al., 1997; and Rasmussen et al., 2013).

Additionally, streams in a poor physical condition are more susceptible to the negative effects of BOD (Biological Oxygen Demand) discharged (Kristensen et al., 2014). Furthermore, studies by e.g. Gibbins et al. (2007) indicate that a correlation between sediment transport and drift of invertebrates can be established. Flooding, on the other hand, is the result of water levels exceeding the bank level. This is primarily a problem for urban and rural areas close to the stream. Therefore, the detention ponds must be designed to reduce the peak flow discharged into the stream in order to avoid hydraulic damage and flooding. The necessary efficient volume available for water detention in a detention pond is calculated based on two parameters: the return period for emergency overflow and the maximum permitted flow rate of the discharge in every other than emergency overflow (Mobley et al. 2013; Mobley and Culver, 2012).

It would require very large detention ponds to reduce the peak runoff from every rain event. Thus, there is a general consensus that the ponds should be designed to discharge emergency overflow at a predefined return period. However, there is no international consensus on which return period to accept. For instance, Fu et al. (2011) mentions return periods between 1 and 10 years. Thus, the pond is allowed to discharge emergency overflow (equal to a direct discharge without reduction of the peak) once within period of 10 years, if 10 years is the accepted return period. In Denmark, the official guidelines recommend a return period for emergency overflow from stormwater detention ponds of five years (e.g. Miljøstyrelsen, 2018). This will be covered further in Section 1.1. Yet, in recent years, the authorities in Denmark more often require the ponds to be able to detain the stormwater for a longer return period of 5 -100 years (Thomsen et al., 2019).

As for the acceptable return period of emergency overflow, there is no international standard for how much the stormwater peak flow has to be reduced in a detention pond. In the USA, UK and Australia, the prevailing practice is to demand that the discharge be equal to the predeveloped runoff (James et al., 1987; Goff and Gentry, 2006; EPA, 2014). The practice in Denmark is for the authorities to make an individual assessment of the stream capacity (Miljøstyrelsen, 2018). A study of the practice of discharge management in the six European countries of Poland, Netherlands, Germany, England, Sweden and Denmark showed that all except England focused on pollution when issuing discharge permits, while England primarily focused on flooding (Koziel, 2018). From this study, it also appeared that there was no common consensus on the approach to issuing discharge permits. In this context, it must be noted that discharge permits in Denmark focus both on ecological parameters and hydraulic parameters, such as flooding. A study by Thomsen et al. (2019) showed this by analysing 37 Danish discharge permits. Historically, Denmark has focused a great deal on flooding, which could be due to the geology of Denmark as a lowland country, and because Denmark is very agriculturally dense. 62% of Denmark is farmed land (Danmarks Statistik, 2019). Thus, there is a high level of public awareness of flooding of both urban and rural areas. Such local geographical differences between the countries might help to explain the differences between their practices.

No matter which approach is used when issuing the discharge permit, the focus should be to respect the resilience and capacity of the stream, and to avoid damage to the stream and the stream habitat. In European countries, this means not to hinder meeting the criteria for good ecological conditions as presented in the European Water Framework Directive (European Commission, 2000). Today, however, there is no general method for defining stream resilience and capacity. Stream capacity is generally defined as a hydraulic capacity defining the limit for flooding. This can be calculated based on a variety of computer models – e.g. the hydrodynamic stream model, MIKE 11 (DHI, 2017). However, the stream also has some level of resilience against the impact of high discharge. In the European Water Framework Directive, the state of the stream is based on the ecological and chemical quality (European Commission, 2000).

The chemical quality is primarily dependent on the concentration of chemicals in the stream, such as oxygen, organic matter, nutrients, pH, xenobiotics, and more. The ecological quality, on the other hand, is dependent on both the physical structure of the stream, such as the stream profile, slope, bed sediment, etc. the possibility for interaction between the stream and the riparian areas, and the chemical conditions (e.g. Grizzetti et al., 2017).

In order to determine how discharge affects the ecology of the receiving stream, it is necessary to assess the impact on the freshwater invertebrates, the fish, the macrophytes, the bentic algae, and the water chemistry. As mentioned, the chemical conditions in the stream are primarily affected by the concentration of different compounds in the stormwater discharged. In Denmark, the prevailing practice is to require wet detention ponds designed according to the standards described in Vollertsen et al. (2012a; 2012b) as a combined retention and detention tool. A wet detention pond consists of a permanent water filled volume (the retention volume), and a storm storage volume (the detention volume or efficient volume). When using wet stormwater detention ponds, the primary treatment of the stormwater happens in the wet retention volume, and the size of the detention volume is negligible in terms of the retention of solids if the pond is designed correctly (Vollertsen et al., 2007). Thus, the retention of substrates is not taken into account when assessing the acceptable discharged flow rate.

The impact of the detention ponds can thus be complicated in terms of physics, chemistry and biology. However, the primary concern is the physical effect, particularly erosion and flooding. If the physical impact is high, it can also be difficult to achieve a good ecological quality (e.g. Hunsaker et al., 1990 and Rasmussen et al., 2017). Mitigating the effects of stormwater discharge would naturally start with a low hydraulic impact, and only then would it be possible to improve the treatment efficiency of the pond. Regarding undesired chemicals in stormwater, it is most important to remove them from the source, and if not removed sufficiently they can be treated at a diluted concentration in the pond.

Regardless of which method is used to quantify the maximum discharge, a focus point should be that, as well as defining an upper limit for the discharge, a lower limit should be defined too. Assuming the mean yearly rainfall is 750 mm/year, for one hectare this is equal to 7.500 m^3/year (in case no precipitation occurs). Assuming that a detention pond discharges continuously every second for a year, the discharge permit could not be lower than 0.24 L/s/ha. Otherwise, the water will accumulate in the detention pond. It is clear that the problems with a *large* discharge is that the stream gets overloaded and flooding and/or erosion will occur (e.g. Konrad, 2003). The problem with a *small* discharge is the increased period of time which must be spent discharging after each rain event. The hydraulic detention time is directly linked to the discharge rate. The prolonged discharge from the ponds may cause increased stream flow for a longer duration in the streams, and this might also be harmful according to Mobley and Culver (2012) and Roesner et at. (2001). The long duration of water detained in the detention pond also increases the likelihood of overlapping/combined rain events detained in the pond. The water from several rain events is accumulated in the pond, which increases the risk of emergency overflow. If the discharge is too small, the risk is that the pond never empties – as described above. In such cases, even a small rain event can result in emergency overflow, since the detention volume has been used. It would be beneficial to obtain more knowledge about the effect of having a a discharge permit which allows only a small flow rate to be discharged. However, monitoring the pond discharge and efficiency (detention time and pond filling) is not standard practice. The long detention time also has other negative side effects on the water discharged from the detention pond – an effect mentioned by Toet et al. (1990) includes increased eutrophication growth of harmful algae. Further effects include increased temperatures, low oxygen concentrations, and an increased pH, as observed by Wium-Andersen et al. (2013).

The solution to protect the stream towards negative impacts from the urban discharges is therefore to issue a discharge permit, which balances the consequences of both high and low discharged flow rates. This shows the necessity of considering stream capacity in order to obtain the correct discharge permit. In Denmark, for instance, this have been done by implementing requirements, about taking the stream capacity into account when issuing a discharge permit, into the national guidelines. This is further described in Section 1.1. However, no clear consensus has emerged about how to paratactically assess the capacity.

1.1. LEGISLATION, PRACTICE AND CHALLENGES IN DENMARK

Denmark represents a good example on how the practice of stormwater management has changed within the last decade. More focus has been put on the stream ecology and not just flooding of surround areas.

1.1.1. LEGISLATION AND PRACTICE

In 1973, the Environmental Protection Act (Danish: *Miljøbeskyttelsesloven*) (The present version: Miljøstyrelsen, 2019a) was passed in Denmark. Afterwards, guidelines for the regulation of waste- and stormwater were formulated based on this law, and in 1974, the first ordinance on the treatment of wastewater (Danish: *Spildevandsbekendtgørelsen*) (Present version: Miljøstyrelsen, 2018) was passed. The authorities which enforced the law and issued the permits for discharging stormwater were then the local authorities in the counties, which later became the municipalities of today. It was, and is, their task to assign the acceptable discharge flow rate.

The 1999 official guidelines for the wastewater ordinance (Danish: *Vejledning til spildevandsbekendtgørelsen*) (Miljøstyrelsen, 1999) explained that the flow rate accepted in the discharge permit should respect the hydraulic capacity of the receiving stream, and that the discharge should also be adjusted according to the physical conditions of the stream. Furthermore, it stated that the discharge of surface stormwater was not allowed to result in a more frequent or widespread flooding of the stream and the riparian areas. Before these guidelines were established, the prevailing practice when issuing a discharge permit was either to accept a direct discharge or accepting a discharged flow rate at 1-2 L/s/ha urban area. Miljøstyrelsen (2019b) states that today, 76% of all discharge points from the separate sewer system are discharging without a detention pond – equal to 11,440 points. The practice of permitting a discharged flow rate at 1-2 L/s/ha is presumably because the authorities equate drainage discharges with urban stormwater discharges. Jakobsen (1946) analysed 20 years of runoff data at 17 flow stations and concluded that the 20-year runoff was 100-200 L/s/km^2, and in order to not over-invest drainage pipes that are too large, the best investment would be dimensioning the pipes for this maximum discharge. Gradually, this practice was adopted in the guidelines and official documents, and Spildevandskomiteen (1998), among other official guidelines, addressed the practice of discharging a fixed flow rate of 1 L/s/ha, but pointed out that the permitted discharged flow rate should not result in an increased 2-year maximum flow event in the streams.

The practice of limiting the discharge to 1-2 L/s/urban ha is also recommended in official water protection plans, such as Vandplan 1.2 (Naturstyrelsen, 2011), which contains the Danish guidelines for implementing the goals from the European Water Framework Directive. It states that, in the case of risk of hydraulic problems in the stream, the discharge permission must by default be reduced to 1-2 L/s/ha (urban area), corresponding to natural runoff. This statement is reformulated in the guidelines for the wastewater ordinance from 2018 (Spildevandsvejledningen, 2018) (Miljøstyrelsen, 2018). Here, Miljøstyrelsen (The Environmental Protection Agency) writes that there is not and will not be any standard practice for assessing the dimensioning of stormwater detention ponds, and thus the discharge permit. However, as a general rule, the discharge permit for stormwater discharge to a stream with hydraulic problems should be reduced to natural runoff corresponding to 1-2 L/s/ha, considering the stream capacity and other potential future stormwater outlets. However, in the case of streams with severe hydraulic problems, it might be necessary to reduce the discharged flow rate further.

The guidelines refer to some of the latest verdicts from the board responsible for complains within the area of environment and food (*Miljø- og Fødevareklagenævnet),* here after “The Board of Complains concerning Environment and Food”. This board processes complaints about discharge permits and decide whether the permit should be upheld or not. Verdicts from “The Board of Complains concerning Environment and Food” must be implemented as guidelines in future permits. In 2015, they made one of their defining verdicts (Miljø- og Fødevareklagenævnet, 2015), which was that the discharge permit should respect the hydraulic capacity in the stream. In this case, two ways of respecting this verdict were mentioned. The first was to have a maximum discharge from the paved catchment which leads stormwater to the detention pond be equal to the *natural runoff*, which is defined as the 2-year maximum area-specific runoff measured in the stream. Alternatively, the authorities should calculate the *stream capacity* and make sure that the discharge will not result in more frequent or widespread flooding of the stream and the riparian areas than runoff from the natural stream catchment. In the calculation, all available data should be considered. Furthermore, the discharge must not interfere with the stream’s ability to meet the goal of good ecological status set by the European Water Framework Directive (European Commission, 2000). Other verdicts have the same content, and some only focus on respecting the hydraulic capacity. However, the consensus in the field of stormwater management is that the discharge permit is based on either the 2-year maximum runoff or a specific analysis of the stream capacity.

The implications of these verdicts are challenging for both the local authorities and the water utility companies. The standard practice of discharging 1-2 L/s/ha made the process of issuing the discharge permit easy for the municipalities and rendered stormwater management planning uncomplicated for the water utility companies. If the water utility companies know the approximate value of the accepted maximum discharge in advance, their projects and investments are easier to plan within their fixed yearly budget. The allowed maximum flow rate in the discharge permit is essential to the size of the stormwater detention pond, and thus also to the establishing and running costs (Figure 1.1).

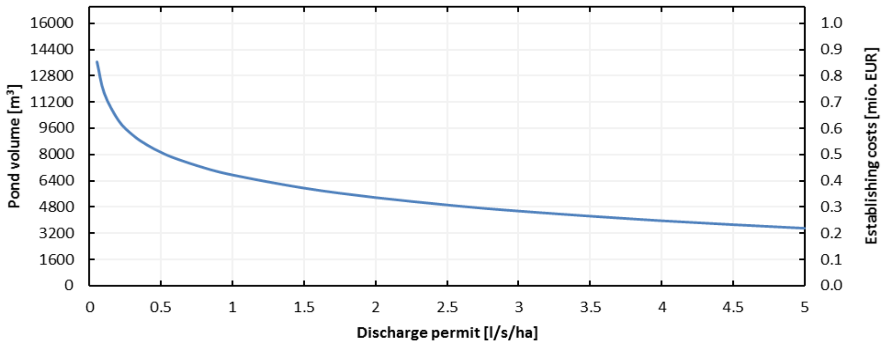

Figure 1.1: *Correlation between discharge permit and the necessary pond volume, and the establishing costs. The correlation is based on calculations from Spildevandskomiteen (2014). The calculations in the example are based on a detention pond which receives stormwater from a paved urban catchment of 10 ha.*

Figure 1.1 illustrates an example of the correlation between the establishing costs and volume of the detention volume and the allowed discharged flow rate for an urban area. The example is based on simple calculations from the Danish wastewater committee's pond dimensioning tool (Spildevandskomiteen, 2014) and in the result, an extra 20% volume to compensate for combined rain events is included. Even though 20% extra volume is not enough to compensate for the accumulation of rain events in case of small discharge permits (approximately <0.5 L/s/ha) as described previously, Figure 1.1 still provides an overview of the correlation between discharge permit and the pond volume and establishing costs. Here, the establishing costs is set to be €66/m^3 (assuming a linear correlation between the volume and establishing costs). As it appears from the correlation, the smaller the allowed discharge rate, the higher the cost. This is a strong incentive for the water utility companies to aim for the largest possible flow rate. Besides the cost of the pond, the size of the detention pond also affects the area reserved for stormwater management, thus also affecting the urban planners. For instance, a larger detention pond may be established at the expense of several building plots, areas reserved for recreational purposes, or on behalf of existing or planned re-established nature. Sometimes, in existing cities, there is no room for large open detention ponds, and thus part of the detention volume must be kept in concrete ponds beneath the terrain. These constructions are about 10 times as expensive as an open stormwater detention pond. Thus, the economical and spatial effects of small discharge permits can be significant. On the other hand, the discharge from the detention ponds should and must respect the stream capacity. Thus, it is of national interest to find a method which accommodates a sustainable way – ecologically as well as economically – of managing stormwater outlets to the nearby streams.

1.1.2. CHALLENGES IN DETERMINING THE STATISTICAL BACKGROUND FOR DISCHARGE PERMITS

As previously mentioned, the Danish national guidelines introduce the term *natural runoff* as a parameter to be taken into account when issuing a discharge permit. In other countries the term *predeveloped flow* is often used to describe the discharge permit. Both is assessing the runoff from the stream catchment

However, in the Danish national guidelines, the interpretation of the term *natural runoff* is often ambiguous and contradictory. The guidelines for the wastewater ordinance describe it as 1-2 L/s/ha, whereas the verdicts from The Board of Complains concerning Environment and Food define it as the 2-year maximum area-specific runoff measured in the stream. Hence, the term has resulted in much confusion. The general, current definition of natural runoff in this context is the 2-year maximum area-specific runoff. Determining the value of this runoff is also problematic, since the natural runoff is dependent on the size and gradient of the stream catchment (examples of this can be seen in Figure 1.2). The 2-year maximum runoff is the size of the runoff from the catchment which, in general, will be exceeded every second year, and it is usually calculated based on a flow dataset of 10 - 30 years (Ovesen et al., 2000).

One of the issues with using this value as the permission for maximum discharge from a detention pond is that detention ponds are often designed for a return period for emergency overflow of 5 or 10 years (Miljøstyrelsen, 2018 recommends 5 years). There is no clear correlation between the return period of a rain event and the return period for a runoff event. However, assuming there is some correlation, the 2-years maximum runoff would not be equal to the natural flow during a long-lasting rain event with a return period of 5 or 10 years. Equally, the 2-year maximum flow is too high to simulate the natural flow during everyday rain events.

As pointed out by Akan (1989), it is not possible to allow a single flow rate and assume that it is always equal to the natural flow. Thus, the wish to mimic natural runoff is not possible with a passive control structure like a flow regulator, a throttling pipe or a sliding valve. Passive regulation allows only one setting point for the discharge, which is the maximum discharge flow rate; and this is usually the flow rate discharged when the pond is filled, namely just before emergency overflow occurs. If a system of passive regulation is implemented, the discharge flow rate is only dependent on the water level in the pond, and it will discharge a higher flow rate when the water levels is high, and a low flow rate as a result of lower water levels.

When setting the permissions for the maximum discharge from a pond based on measured data of the natural runoff measured in the stream, the challenge is that the flow measured in the stream is the sum of the runoff contribution from the entire stream catchment. Usually, the observation site in the stream is not where the discharge is planned to be released. Most of the measurement stations in Denmark are placed in the downstream part of the stream systems, because their purpose has been to measure total runoff in order to make calculations of yearly overall nutrient transport from the catchment area to downstream water bodies like lakes and coastal areas. As illustrated in Figure 1.2, the position of the flow measurement station used to determine the natural area-specific runoff is very important for the result, and thus for the discharge permit. This correlation between the catchment and the resulting flow has also been investigated by e.g. Høybye (1991)

The flow data analysis in Figure 1.2 is the 2-year maximum area-specific runoff based on continuous flow measurements from 166 flow stations distributed across Denmark.

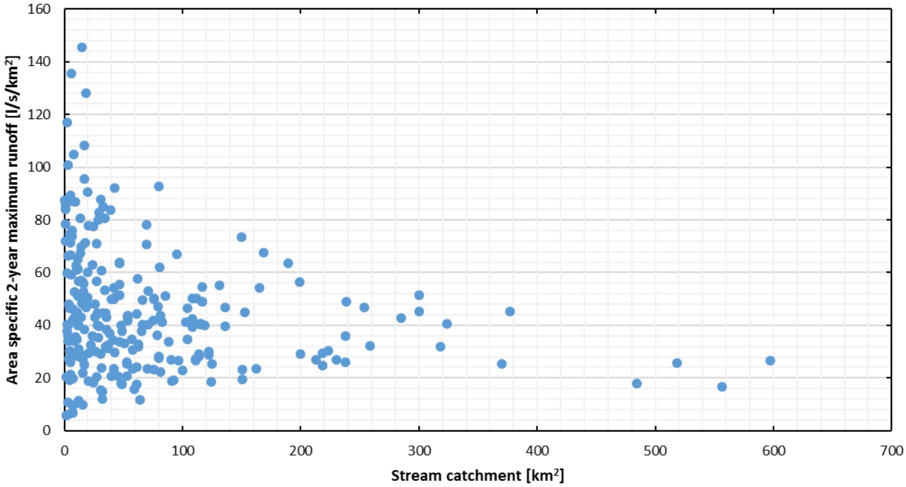

Figure 1.2: *The area-specific 2-year maximum runoff and stream catchment from 166 measurement stations in Denmark.*

These results show that there is some correlation between the 2-year maximum area-specific runoff and the size of the catchment. It also appears that the results are rather scattered, especially in the small catchments. There are several explanations for the scattered pattern, but two of the primary reasons could be the different types of catchments and the temporal resolution of the data used.

In small catchments, the runoff measured in the stream clearly reflects whether the stream primarily receives groundwater or surface water, and whether the runoff comes from a lake, an area with large infiltration, or an area with a large surface or sub-surface runoff. In a larger catchment, this effect will be hidden due to the contributions from many different types of catchment.

Furthermore, the way stream flow data is usually collected in Denmark is through daily mean values (the mean of 24 hours). Thus, the 2-year maximum area-specific runoff data in this analysis, and the data used in the discharge permits, is based on daily mean data. Had data with a temporal resolution of 10 to 15 minutes been available, it would be expected that the correlation would have looked quite different. In this case, the area-specific runoff from many of the smaller catchments would probably have been higher due to the rapid and short reaction time in these. The coarse temporal resolution of the daily mean values means that the runoff value is an average of the larger variations during the day. This effect is not as significant in flow measurements taken in a larger catchment due to the longer reaction time and less rapid changes in flow.

Thus, it is evident that data from a measurement station far downstream will most often not be a good representation of the whole stream, as it will differ greatly from data collected from a point further upstream. If the focus is to mimic the natural runoff when discharging from a detention pond, the discharge from the detention pond should not simulate the resulting streamflow; rather, it should simulate the natural runoff from the sub-catchment, from which the pond receives the stormwater. Such a practice will necessitate a much better systematic analysis of the catchment runoff and a spatially and temporally denser measurement system. Furthermore, a complete imitation of the natural (pre-development) flow would require active control of the discharge, since the standard passive flow regulation methods are not able to do so.

The main conclusion from the analysis presented in Figure 1.2 is that issuing discharge permits based on flow data from the downstream part of the system often will result in unnecessarily restrictive requirements. Often, the receiving streams have capacities much larger than the discharge allowed in the permissions, because the natural runoff from the catchment would presumably be higher.

Furthermore, many streams in Denmark have historically been regulated in order to increase their drainage capacity (Brookes, 1984). Baattrup-Pedersen (2000) states that more than 90% of the Danish streams are regulated. Thus, many streams have larger capacity compared to their natural flow variation – they are either too deep or too wide compared to natural streams. This might also affect the approach in terms of determining the correct discharge to the streams. Having a close to natural discharge pattern in an unnatural stream profile might not achieve the goal of supporting the good ecological status of the stream. Because the physical conditions have been changed from the natural geometry, a natural runoff will no longer be able to describe the optimum hydraulic conditions. This might be the reason why many municipalities and water utility companies are now using the approach of calculating the stream capacity. Due to the reasons previously mentioned, this is often defined as the capacity with respect to flooding and, in some cases, the resilience against erosion. However, it is a challenge to calculate the level of erosion / sediment transport, and it is a focus of this project to address this challenge.

Assessing the capacity naturally opens for considering the here-and-now capacity, which is the difference between the maximum capacity and the “unaffected”/natural streamflow which varies in the stream. Could a discharge strategy be designed to actively include this varying capacity and utilise the difference in reaction time between the urban catchment stream catchment?

1.2. RESEARCH QUESTIONS

From the analysis above, it is clear that important knowledge is missing in order to improve the design of stormwater detention ponds and to truly evaluate the hydraulic impact of discharge into streams. Three questions sum up the initial motivation behind this project, and these will be the main focus of this work:

I. How do we get simple, cost-effective and reliable measurements of the *actual* discharge from stormwater detention ponds?
II. How do we evaluate the impact of the discharge on the stream?
III. Which approach to controlling the discharge could improve the existing operation of stormwater detention ponds?

This is not an exhaustive list of the topics and issues which relate to the interactions between detention ponds and streams, but they represent important improvements to present-day management of this area. To address these topics, a research hypothesis has been formulated and will form the basis for three papers (Appendix I – III):

> *It is possible to switch from the present maximum discharge permission methodology to a flexible approach where the actual here-and-now stream capacity determines the discharge from the stormwater detention pond. This could be done in such a way that it benefits both the stream and the operation of the pond.*

More specific research questions have been formulated in order to guide the working process:

1. **Which hydraulic characteristics do the outflow regulators exhibit during rain events?**
   a. Does there exist a consistent relationship between water level and discharge flow?
   b. To what degree do the hydraulics of the flow regulators represent the discharge permissions for the detention pond?

2. **How is stormwater discharge (increase of the flow) correlated with erosion/sediment transport in the stream?**
   a. Is a threshold value for sediment transport of different particle sizes a realistic measure of when sediment transport occurs?
   b. Can a detailed hydrodynamic stream model be used to predict the sediment transport which results from a discharged flow rate from a detention pond?

3. **Can information about the here-and-now stream capacity of the receiving stream improve the discharge strategy?**
    a. Is it possible to minimise the negative effect of stormwater discharge by controlling the discharge based on the actual stream capacity?
    b. Would the implementation of storm forecasts improve the efficiency of a control strategy solution and result in fewer emergency overflow events?

CHAPTER 2. METHODOLOGY

The core method in this study was to conduct full-scale experiments. These relied on data from real stormwater detention ponds which discharged to actual streams, thus ensuring that the results were directly comparable to actual operational conditions. However, a disadvantage is the possible difficulties in translating the results into general conclusions which are directly applicable in other detention pond setups. The solution was to choose a detention pond setup which was operational, but which also had the possibility to function as a laboratory setup with fully hydraulic control. With such a setup, it was possible to both monitor the existing discharge strategy and to test the effect of an altered discharge strategy.

In order to monitor the existing conditions, knowledge of the existing discharge and resulting flow in the stream was necessary. The traditional way of measuring the pond discharge is either to measure the flow upstream and downstream from the point of discharge in the stream, or to install a flowmeter in the outlet from the pond, as described in **Paper I**. However, a flowmeter is an expensive and complicated instrument to install and maintain. Therefore, as a compromise, we used a water level sensor installed in both the pond and in the stream downstream from the point of discharge instead. The water level sensor was installed downstream from the point of discharge in the stream in order to measure the resulting stream flow. Likewise, a water level station was installed in the stormwater detention pond on order to monitor the discharge. The idea was that it would be possible to calculate the discharge from the pond based on knowledge about the pond geometry and the decrease in water level. Additionally, it would be possible to determine the inflow based on the increase in water level.

Four ponds were selected for monitoring. Since all four ponds were regulated with passive regulation devices – three with a water brake and one with a pipe – all of them should in principle have a fixed rating curve for the discharge (e.g. Pitt, 2004).

The monitoring setup in the four locations was identical, consisting of an OTT pressure sensor (OTT PLS, 2018) combined with an YDOC logger (YDOC, 2019) mounted in the stream and the detention pond, as illustrated in Figures 2.3, 2.4, 2.5 and 2.6. A further description of the setup is presented in **Paper I**. The logging interval was generally 10 minutes, but it was adjusted depended on the reaction time of the system. Data from the loggers was sent to an FTP-server every three hours and presented online. Thus, it could be assessed and used by the municipality and water utility company. The data from this setup is used in **Papers I – III**.

At each site, a rating curve was established for both the stream and the detention pond. In order to translate the time series of the measured water level into a discharge flow rate, the mass balance method described in **Paper I** was used. During dry weather and under ideal conditions, the only parameter affecting the water level in the pond is the discharge. Thus, the decreased water level after the end of a rain event could be translated into a discharged flow rate based on knowledge about the position of the water table and the pond geometry (described in **Paper I**). Knowledge of the pond geometry was obtained based on the design material of each pond, combined with information from the 2015 0.4 meters terrain model (SDFE, 2019). In one pond, the geometry was specified based on GPS measurements. The discharge flow rate from each rain event analysed was verified using flow data from the stream. The exact rating curve was obtained by processing the data from a minimum of 10 rain events. Examples of the established rating curves are presented in **Paper I** and **Paper III**.

In the stream, the rating curves were established based on a series of flow measurements during different conditions in the stream. Flow measurements were made for a range of different water levels, in order to setup the rating curve, and during every season of the year, in order to quantify the effect of weed growth. Based on the method of proportionality (Raaschau, 1991), those spot flow measurements were used to convert the measured time series of the water level into a time series of flow.

The flow measurements in the streams was conducted with an OTT C2 flowmeter (OTT C2, 2019) (Figure 2.1)

Figure 2.1: *OTT C2 flowmeter. a) shows the flow meter with a C6 propeller and b) shows the measurement setup in a stream.*

2.1. EXPERIMENTAL SITES

During the process of choosing the experimental sites, it was prioritised to choose a stream with only one detention pond discharging to it. Thus, it was possible to formulate a simple control strategy which only needed to manage two contributions, namely the stream catchment runoff and the pond discharge. Another criterion was the size of the stream catchment, as the streams used in the study should be different from each other. This is relevant because it would be expected that the runoff from a small stream catchment would have a faster reaction and a shorter duration compared to a larger stream catchment. Hence different effects of the pond discharges would be observed. Thus, the stream catchments of the observation sites ranged from 0.7km^2 – 12 km^2. The positions of the observation sites are presented in Figure 2.2; they are located in Vejle, Aarhus, and Randers, respectively. The reason for these locations is that the project is carried out in collaboration with the municipality and water utility companies from these three locations. In Aarhus, two locations are monitored. Here, we chose two streams of approximately the same size, because it would be interesting to compare their results.

Figure 2.2: *Position of the four observation sites in Randers (Svejstrup Bæk), Aarhus (Hovedgrøften and Beder Bæk) and Vejle (Polsterbæk) in Denmark*

2.1.1. RANDERS – SVEJSTRUP BÆK

In Randers, the monitoring location is in the stream Svejstrup Bæk. Svejstrup Bæk has a stream catchment of 12 km^2 at the point of discharge, and thus, it is the stream with the largest catchment in this study. The stream measurement station is located around 600 meters downstream from the point of discharge. The locations of pond and stream measurement stations are presented in Figure 2.3a and 2.3b respectively. The detention pond which discharges to Svejstrup Bæk receives stormwater from a 30 ha industrial area. The discharge permit from the detention pond is 50 L/s and it is regulated by a water brake.

Figure 2.3: *Measurement station in Randers. a) illustrates the measurement station in the detention pond, and b) illustrates the measurement station in the stream Svejstrup Bæk.*

The water level in both the detention pond and in Svejstrup Bæk was monitored from July 2016 to December 2019. 16 flow measurements were conducted in order to set up the rating curve for the stream flow.

2.1.2. AARHUS – HOVEDGRØFTEN

In Aarhus, there are two observation sites. Hovedgrøften receives discharges from two detention ponds; one discharges at the top of the stream and one 3.9 km downstream. The downstream detention pond is the one monitored in this project. This detention pond receives stormwater from an urban catchment of 59 ha (the measurement station is illustrated in Figure 2.4b. The discharge permit for this detention pond is 95 L/s, and it is regulated by a water brake (Figure 2.4c). At the point of discharge, the stream catchment is 6 km^2, and the measurement station is placed 30 meters downstream (the measurement station is illustrated in Figure 2.4a).

Figure 2.4: *Measurement station in Aarhus (Hovedgrøften). a) illustrates the measurement station in the stream Hovedgrøften, and b) illustrates the measurement station in the detention pond which discharges to Hovedgrøften. c) illustrates the water brake in the outlet from the detention pond.*

The water level in Hovedgrøften was monitored from July 2016 to December 2019, and 20 flow measurements were taken in order to set up the rating curve for the stream flow. The detention pond was not established before the end of 2016; thus, the monitoring of the detention pond took place in the period December 2016 – December 2019.

2.1.3. AARHUS – BEDER BÆK

The other observation site in Aarhus is in the stream Beder Bæk. Beder Bæk has a stream catchment of 4.5 km^2 at the point of discharge, and the measurement station is placed 20 meters downstream (Figure 2.5c). The detention pond receives stormwater from an urban catchment of 12 ha (the measurement station is illustrated in Figure 2.5b). The discharge permit for the detention pond is 75 L/s, and it is regulated by a water brake (Figure 2.5a).

Figure 2.5: *Measurement station in Aarhus (Beder Bæk). a) illustrates the water brake in the outlet from the detention pond, and b) illustrates the measurement station in the detention pond which discharges to Beder Bæk. c) illustrates the measurement station in the stream Beder Bæk.*

As for Høvedgrøften, the water level in Beder Bæk was monitored from June 2016 to December 2019, and 21 flow measurements were taken in order to set up the rating curve for the stream flow. Here, too, the detention pond was established at the end of 2016; thus, the monitoring of the detention pond took place in the period December 2016 – December 2019.

2.1.4. VEJLE – POLSTERBÆK

The stream Polsterbæk is located in Vejle. Polsterbæk is a small stream with a stream catchment at the point of discharge of 0.7 km^2.The monitoring station in the stream is situated 90 meters downstream from the point of discharge (Figure 2.6c) and the measurement station is illustrated in Figure 2.6a. The detention pond which discharges to Polsterbæk receives water from a 40 ha urban area, and the discharge permit for the pond is 80 L/s. The measurement station is illustrated in Figure 2.6b.

Figure 2.6: *Measurement station in Vejle. a) illustrates the measurement station in the stream Polsterbæk. b) Illustrates the sliding valve installed in the outlet from the detention pond which discharges to Polsterbæk, and c) illustrates the measurement station in the detention pond which discharges to Polsterbæk*

Monitoring in both the stream and the detention pond started in June 2016. During the first two years, the pond was regulated with a throttling pipe. In the period of March to July 2018, the detention pond was dredged, and the flow regulation method changed to a sliding valve. During this process, the water utility company Vejle Spildevand A/S installed a siding valve, which could be controlled. Thus, this detention pond was used in all future experiments testing control strategies and thresholds of erosion.

Due to the dredging period, the water level was monitored during two periods: from June 2016 to March 2018, and again from July 2018 to December 2019. The water level in the stream Polsterbæk was monitored from June 2016 to December 2019. 34 flow measurements were taken in order to set up the rating curve for the stream flow and in order to validate the rating curves for the two flow regulation devices in the detention pond.

2.1.5. SELECTION OF PRIMARY EXPERIMENTAL SITE

Besides studying the effects of the existing discharge strategy, another of the focus points of this project was to determine the conditions which lead to the threshold of sediment transport – both for suspended transport and near-to-bed transport. This was investigated in **Paper II** and **Paper III**. Any of the ponds could have been used for the main bulk of the experiments. However, due to the effort required in order to do the same experiments at all the different sites, it was decided to select one as the primary site and keep the rest as reference sites for future work.

The detention pond in Vejle and the stream Polsterbæk was chosen as the primary site. The reason for choosing the Polsterbæk site was that Polsterbæk is heavily influenced by the discharge from the pond, so it is possible to study many variations in flow and sediment transport. During dry weather periods, the flow in Polsterbæk is rather stable and low. Thus, it would be possible to control the flow in the stream by adjusting the discharge from the detention pond. Furthermore, the water utility company in Vejle changed the design of the detention pond in 2018, when they installed a sliding valve. This made it possible to control the discharge from the detention pond, and thus Polsterbæk could be monitored and controlled like an in-situ flume. The primary drawback of this site is that is not a typical Danish stream due to its steep slope of approximately 30 ‰ and the almost mountainous characteristics of the surroundings. However, the site allows for the possibility to do systematic experiments with sediment transport, which would not be possible at the other sites.

2.2. SEDIMENT TRANSPORT EXPERIMENTS

Due to the regulation of the detention pond, it was possible to measure the sediment transport (both the suspended transport and the bed sediment transport) which occurred as a result of different discharged flow rates. Thus, it was possible to test whether it was possible establish a correlation between the discharge and sediment transport. The aim of this was to determine the threshold of sediment transport in Polsterbæk. These results are presented in **Paper II**. The threshold was used as a control parameter in the controlled discharge presented in **Paper III**.

In order to design and analyse the experiments, it was necessary to know the geometry and sediment composition of Polsterbæk. Likewise, the rating curve for the sliding valve had to be established in order to regulate the discharge. Furthermore, a suitable method to quantify the sediment transport had to be found.

2.2.1. EXPERIMENTAL SITE – POLSTERBÆK IN VEJLE

A stream survey was conducted in order to describe the stream geometry (slope, width and depth). The stream was mapped out by measuring the cross-section of several profiles throughout the stream. It was not possible to do this with a GPS due to interference with the tree canopies. Therefore, an electronical levelling device was used (Figure 2.7). The measurements were compared to the digital elevation model from 2015 (SDFE, 2019) in order to validate, and this showed a good correspondence. Thus the measured profiles was supplemented with data from the terrainmodel. The spatial resulution of the measurements was relatively dense due to the variations of geometry in Polsterbæk. The longitudinal profile is shown in Figure 2.8. Knowledge of the geometry is used, for example, to set up a MIKE 11 model in **Paper III**.

Figure 2.7: *Illustration of the equipment for measuring the cross-sections of Polsterbæk. a) shows the electronical levelling device, and b) shows the post used to register the vertical variations in the stream.*

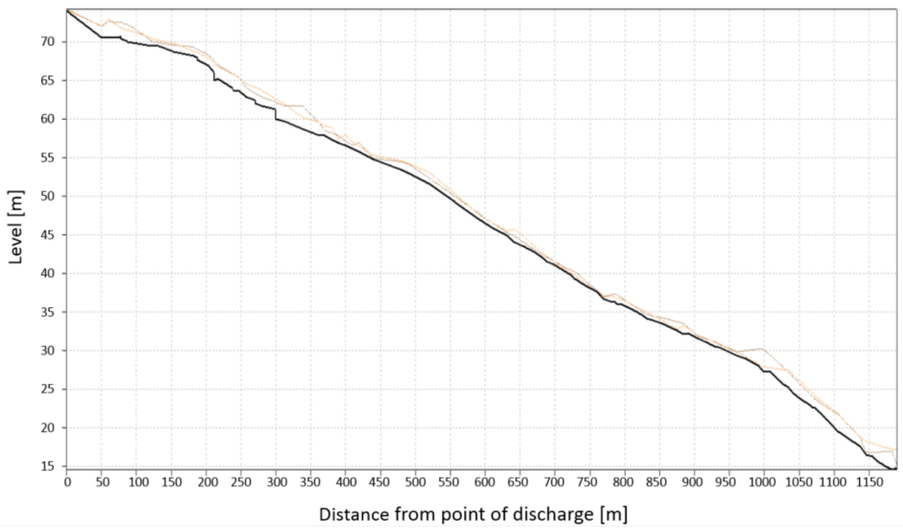

Figure 2.8: *Illustration of the longitudinal profile of Polsterbæk at the point downstream from the outlet from the pipe. The solid line is the bed and the dotted lines are the banks.*

Polsterbæk is situated in a forest and, as mentioned previously, it is relatively steep compared to a general Danish stream. The bed consists of a heterogeneous mix of clay, silt, sand, gravel, stones and rocks. An example of the bed is illustrated in Figure 2.9. Both the bed sediment composition and geometry are highly diverse in Polsterbæk, and during dry weather flow, it is not unusual to see sand depositions in some sections of the stream. Some of the sand observed in the stream is expected to originate from the terrain of the stream catchment which contributes to Polsterbæk. The terrain sloping towards the stream has an equally high slope, and after a storm event, new erosion trenches often appear. During low flow conditions, the stream flow ranges from 0.5 to 2 L/s, so the sediment transport is approximately equal to zero.

Figure 2.9: Illustration of the diverse conditions in Polsterbæk.

The detention pond which discharges to Polsterbæk was, as described in Section 2.1.4, changed from a throttling pipe to a sliding valve in 2018, thus making it possible to control the discharge from the detention pond. When the sliding valve was installed, it was regulated by a turning wheel as illustrated in Figure 2.10a. This made it possible to slide the gate, as illustrated in Figure 2.6b. The construction of the manhole, illustrated in Figure 2.10, ensures that the water level at the inlet side of the regulation is equal to the water level in the detention pond. When the water level is below the crest of the separating wall, the flow is regulated by the sliding valve. However, any water above the crest is discharged in an almost unregulated manner to the outlet side, which is connected to the stream by a non-limiting pipe. In order to be able to regulate the sliding valve automatically, the turning wheel was replaced with a battery-powered motor (Figure 2.10b and c). This motor was connected to a microcontroller, which received real-time monitoring data of the position of the sliding valve and the water level. Based on a defined rating curve of the sliding valve, the motor controller was able to calculate the discharge flow rate at any given moment.

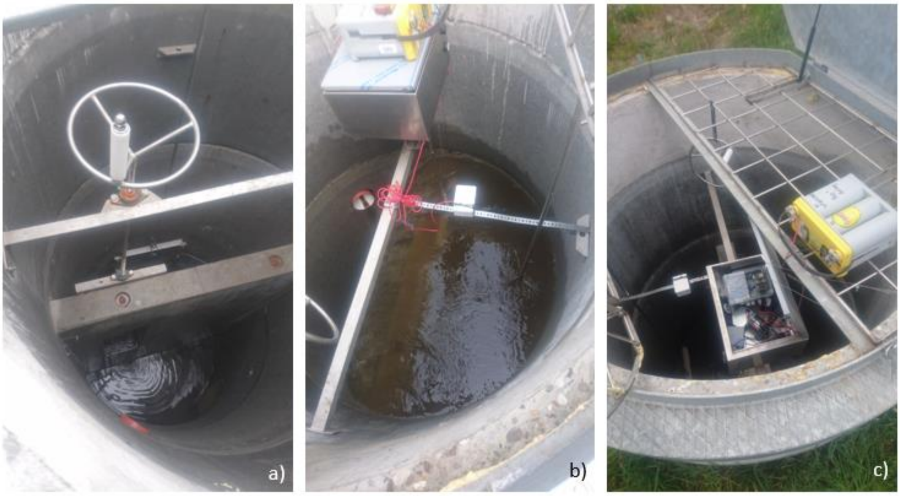

Figure 2.10: *Illustration the manhole and flow regulation in the detention pond in Polsterbæk. a) shows the original regulation of the sliding valve with a turning wheel, b) shows the box containing the motor controller for the position of the sliding valve (in this image, there is an emergency overflow). c) shows the box containing the motor controller for the sliding valve.*

The rating curve was established based on the mass balance method described in **Paper I** and Torricelli's theorem (Otto et al., 2018), as described in **Paper III**. In order to make the rating curve applicable to all openings of the sliding valve, it was established for several positions, and the motor controller for the sliding valve was calibrated based on the results. In contrast to the experiment presented in **Paper I**, which was based on three ponds regulated with water brakes and the pond in Polsterbæk, at that time regulated with a throttling pipe, in this experiment it was possible to use the sliding valve to close the outlet. Thus, it was possible to fill the detention pond with stormwater during several rain events. Hereafter, during dry periods, the sliding valve could be opened to a specific position, and the rating curve for this position could be established with a minimum of other processes affecting the results. Levels of discharge from the pond which occurred as a result of different opening positions of the sliding valve are illustrated in Figure 2.11.

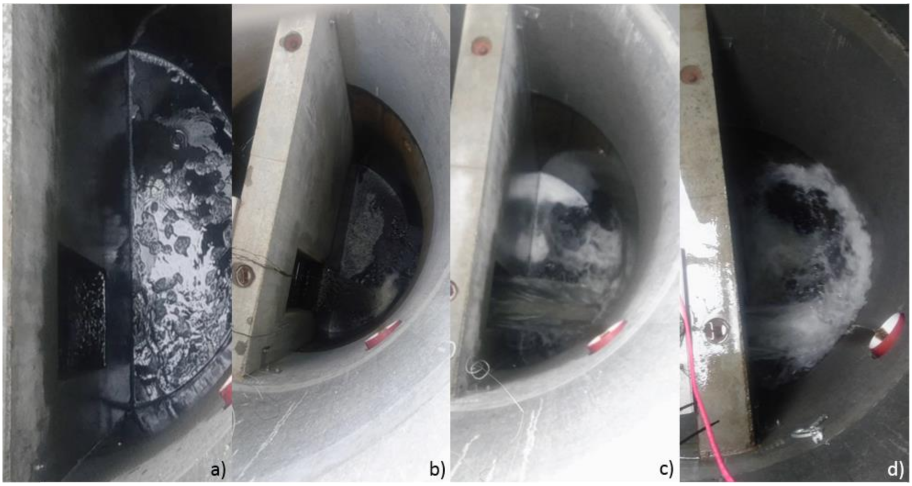

Figure 2.11: *Shows the discharge from the detention pond as a result of increased opening positions of the sliding valve.*

2.2.2. BED SEDIMENT SAMPLER

There are many ways to measure bed sediment transport. Rickemann and McArdell (2007) divide them in four categories: 1) trapping sediment in detention basins, 2) measuring the movement of tracer particles, 3) collecting the moving particles in a trap, and 4) indirectly determining the transport by measuring the particles passing a sensor at the stream bed. In order to be able to do analyses of the sediment in the laboratory after the transport experiment, the method chosen was to collect the transported bed sediment in a pressure difference trap. The trap selected was a Helley Smith trap (illustration of trap in Figure 2.12), which is also used by e.g. Leopold and Emmett (1984) Gomez (1991), and Ferguson (2003). The traditional Helley Smith sediment trap has a 8.9 * 8.9 cm inlet nozzle size. However, Helley and Smith (1971) tested several versions of the sampler, and concluded that scaling the sampler did not matter for the sampling efficiency. The traditional size of the Helley Smith sampler was too large for Polsterbæk; thus, a downscaled version of the sampler was produced for these experiments. This sampler was downscaled to 3/5 of the original size.

A few changes to the design were introduced during the production and testing of the sampler. According to Bunte et al., 2008 the movement of the sampler through the water column in the vertical direction when placing and removing the sampler causes uncertainty in the sampling result, since the movement often "pushes" water and sediment into the sampler. The shorter the period of measuring, the larger the error. In order to avoid this measuring error, the samplers were in this study fixed to a plate anchored to the streambed, which is also recommended in Bunte et al. (2004). Thus, the sampler itself stays in the stream throughout the entire period of measuring and only the sampling bag (Figure 2.13) is removed and replaced with another – the final design is illustrated in Figure 2.12. The trap is 3D printed in ABS plastic. Thus, it is easy to produce more traps and traps in different sizes, if experiments were to be made in another stream.

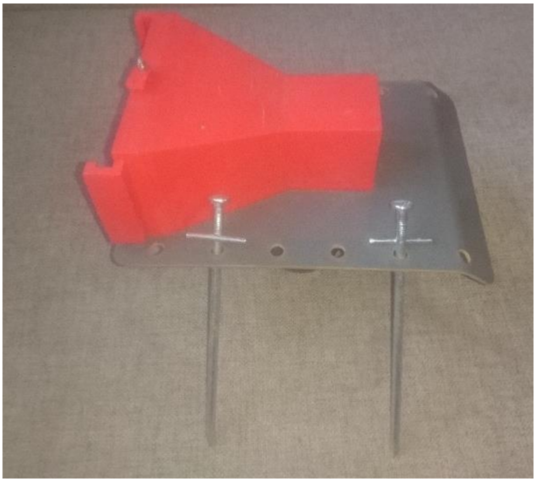

Figure 2.12: *The downscaled version of the Helley Smith sampler – fixed to a plate which can be anchored to the bed.*

The sampling bag was designed in accordance with the traditional design from Helley and Smith (1971). One of the bags used in the experiments is illustrated in Figure 2.13. The bottom threetangle and the two sides are made of 100 µm nylon mesh in order to retain the sediment, and the top threetangle consists of a 250 µm nylon mesh in order to let the water flow through the top.

Figure 2.13: *One of the sampling bags from the Helley Smith sampler used in the experiments.*

Most studies which have used Helley Smith samplers have been conducted in larger streams than Polsterbæk. Recommendations for the optimal distance between traps in the profile are described by e.g. Emmet (1980) and Bunte (2007), who recommend a distance somewhere between 0.4 and 1.2 meters. The mean width of Polsterbæk is approximately 1.5 meters; thus, this can be obtained by using one or two samplers. Studies by e.g. Frings and Vollmer (2017), Leopold and Emmett (1984), Gomez (1991) and Ferguson (2003) showed some differences between sediment transport in sand-bed streams and gravel-bed streams, because the sediment transport is more uniform in the sand-bed streams. This is because gravel bed streams often have a wider grain size distribution. Because of the sorting of the grain sizes, both the shear stress and the critical shear stress varies within the cross section, thus resulting in variation of the sediment transport within the cross section. In sand bed streams, the grain size is more homogenous, and so is the shear stress, given that the sediment transport in a sand bed stream often occurs in the full cross section. Due to Polsterbæk's mixed streambed substrate consisting of stone, gravel, sand, silt and clay, two samplers were placed in each profile in order to cover the largest possible part of the profile. The samplers were placed with an approximately even distance between the bank and the other sampler (setup illustrated in Figure 2.14).

Figure 2.14: *Setup of Helley Smith bed sediment samplers in a profile in Polsterbæk.*

According to Hoey (1992), the sampling time must be regular or systematic in order to interpret the results usefully. Since the sampling strategy affects the type of results obtained, the strategy must reflect the scale of transport that is the object of the study. Furthermore, the filling of the bag had to be considered, so as not to decrease the trapping efficiency. Helley and Smith (1971) showed that the filling of the bag of up to 2/3 had no considerable effect on the velocity in the nozzle, or on the sampling efficiency. Tests in Polsterbæk showed that the sediment transport had to be very high for a long duration of time in order to fill the bag to more than half the available volume. Thus, the sampling time in these experiments was between 30 and 60 minutes depending on the factors being investigated.

2.2.3. SUSPENDED SEDIMENT SAMPLING

In order to measure the suspended transport in the stream, water samples were collected continuously during the experiments. This was done by collecting water in a 2 L urine bag. In the first experiment, the experimental setup was as presented in Figure 2.15, pumping the water from the stream into the urine bag (**Paper II**). In the other experiment (**Paper III**), water samples were extracted from the stream using a plastic syringe and transferred to the urine bag. During both experiments (**Paper II** and **Paper III**), the turbidity was also measured in order to gain a better temporal resolution of the transport using a WTW turbidity meter WTW (2017). Henley et al. (2000) found a good correlation between the suspended sediment transport and the turbidity. A similar correlation was also found in this study.

Figure 2.15: *Illustration of the experimental setup measuring the suspended sediment transport in* ***Paper II.***

2.3. ANALYSIS OF IN-SITU SEDIMENT TRANSPORT EXPERIMENT

In-situ sediment transport measurements was made in both **Paper II** and **Paper III**. In **Paper II,** experiments to estimate the threshold of sediment transport were performed, and in **Paper III,** the variation in the sediment transport within the stream was assessed.

In order to determine the threshold of sediment transport in **Paper II**, sediment transport was monitored in two profiles downstream from the point of discharge – both within 100 meters of the point of discharge. In the experiment, the sediment was sampled during different streamflow conditions. The first experiment was a reference experiment with zero discharge, and hereafter, the discharge was increased step by step with a total of eight steps. During each step, which consisted of a period of 30 minutes, both the suspended and bed sediment transport was collected, as described in Sections 2.2.2 and 2.2.3. After the experiment, the sediment collected in the bed sediment samplers was dried and sieved in a sieving nest (Figure 2.16a). The mass of sediment caught in each sieve was quantified, and a sediment particle size distribution was established in order to compare the sediment samples. An example of the sieved data is shown in Figure 2.16b. In order to quantify the organic content in the sediment samples, subsamples were baked for 550ºC in order to burn the organic matter. Examples of the subsamples burned are shown in Figure 2.17. Additionally, the mass of the suspended sediment collected was quantified by filtering the sediment samples through a glass fiber filter.

Figure 2.16: *a) is the sieving nest used to determine particle size distribution in* ***Paper II****, and b) is an example of the sieved samples from the sediment transport experiment.*

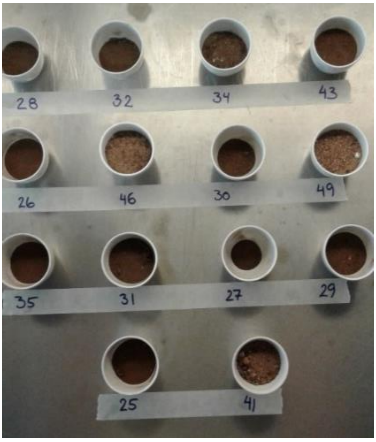

Figure 2.17: *Example of the sediment samples after 20 hours at 550ºC.*

Besides establishing a correlation between the discharged flow rate and sediment transport, in this case both the transported mass and the particle size transported, the purpose of the experiment was to test established threshold models in order to determine which would be the best fit for a stream like Polsterbæk. If one or more models fit the measured data, it would not be necessary to conduct the transport experiments in every stream, and the discharge which results in the threshold of sediment transport could be calculated. Therefore, 11 threshold models were tested, five focusing on shear stress and six focusing on stream power. Petit et al. (2005) suggested that two or more methods should be tested when evaluating sediment transport, in order to compare the results. Two of the best described approaches are shear stress and stream power. The results of the comparison are presented in **Paper II**.

Based on the experiment in which the discharge was gradually increased, thus resulting in the sediment transport presented in **Paper II**, the threshold of sediment transport was found for the monitored part of the stream. However, it is important to determine whether the effect of a discharge is local at the upstream part of the stream, or whether its impact can also be detected further downstream. Hence the monitoring of the stream was intensified by installing water level monitoring equipment in three stations further downstream from the point of discharge of 300, 500 and 700 meters, respectively. **(Paper III**). Those were used to monitor the water level caused by different discharge patterns, and to evaluate whether the peak effect of a discharged volume of water was gradually reduced throughout the stream.

The traditional way of estimating the distribution of the risk of sediment transport and the effect of a discharged pulse of water is through the use of dynamic hydraulic models like MIKE 11. They make it possible to describe the hydraulics in the stream based on the stream geometry. A MIKE 11 model was set up based on an in-stream survey described in Section 2.2.1

In order to calibrate the model and to measure the effects of discharge in all the four measurements stations established, an experiment in which the same volume of water was discharged at two different flow rates was performed. The sediment was then sampled as described in Sections 2.2.2 and 2.2.3. It was collected under three different flow conditions: without discharge, discharging 25 L/s for an hour, and discharging 100 L/s for 15 minutes (measuring for an hour). Afterwards, the reference conditions with no discharge were repeated.

During the experiment, sediment transport measurements were taken, focusing on both bed sediment and suspended sediment. Based on the results, a correlation between discharge and sediment transport could be established, and the station with the highest sediment transport could be pointed out.

Based on the water level results from the experiment, the MIKE 11 model was calibrated. The model was used to simulate a discharge from the detention pond and to calculate the shear stress in the stream. Thus, the locations with the highest shear stress values could be identified. The results of the experiment were used to validate this.

Furthermore, the MIKE 11 model was used to estimate the capacity in relation to flooding. These results can be used to identify the critical locations in the stream, and thus the locations with the lowest capacity for either sediment transport or flooding. Those sections should be the focus points when quantifying the capacity of the stream in relation to discharge, a necessary step when following the official guidelines to the ordinance of wastewater (Miljøstyrelsen, 2018). (described in Section 1.1.1).

2.4. CONTROLLING THE DISCHARGE

The results from the sediment transport measurements in **Paper II** and **Paper III** were used to evaluate the existing discharge strategy of regulating the discharge flow through a sliding valve set in a fixed position; this is defined as passive control. Furthermore, four active control strategies were evaluated. Three of the four active control strategies were based on the same principle, illustrated in Figure 2.18. Here, the capacity in the stream is taken actively into account in the control of the discharge. Thus, the focus is not only on minimising the discharge, but on minimising its impact by actively measuring the result of the discharge and acting on it.

The capacity is estimated based on knowledge about the threshold of sediment transport and the threshold of flooding – the lowest of the two defines the streamflow capacity. Assuming a fixed and constant discharge from the detention pond (e.g. 1 L/s/ha), the discharge is unaffected by the existing streamflow and the capacity. Thus, during low flow events, only a small part of the capacity is utilised, whereas during high flow situations, when the capacity may be depleted due to a large runoff from the stream catchment even a small discharge might excite the stream capacity, as illustrated in Figure 2.18. If the discharged flow rate is controlled based on the stream capacity, a higher discharge flow rate would be accepted in periods when the streamflow is low. However, if the streamflow is high, the discharge would be decreased. In many stream systems, the runoff from the stream catchment is a slower process than runoff from the urban area, as described in Chapter 1. Thus, it will be possible to use the low flow period before the stream catchment runoff to discharge the water from the detention pond, thus ensuring a more efficient strategy - a strategy ensuring a faster discharge of the stormwater volume, thus detention volume is available for the next rain event. Figure 2.18 shows a theoretical example whereby the accumulation of water from two rain events in the detention pond is avoided by actively controlling the discharge. Furthermore, the passive control results in a period of the streamflow exceeding the capacity, which was also avoided by the active control.

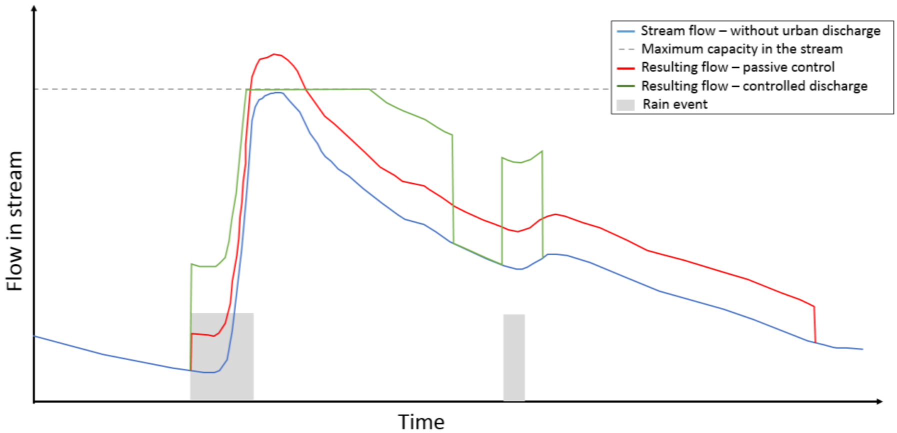

Figure 2.18: *Illustration of the difference between controlled discharge and a fixed discharge flow rate.*

In **Paper III**, five different discharge strategies were tested in order to compare them and determine whether it was possible to improve the conditions of the existing discharge strategy, as well as determining which was the best for balancing the impact in the stream with the efficiency of the detention pond. A computer model was developed in order to compare the different discharge strategies based on the exact same boundary conditions and make a systematic evaluation of the results.

The following evaluation criteria were considered:

- The amount of time the resulting streamflow exceed the stream capacity
- Number of overflow events
- Peak flow discharge
- Duration of overflow
- Volume of overflow
- The amount of time the pond was empty (with the maximum volume available to detain a new rain event)

A volume balance model was formulated on the basis of the paved urban area, the pond geometry and time series data on the rain intensity and the unaffected streamflow for the 3.5-year monitoring period. Here the unaffected stream flow is defined as the flow in Polsterbæk corrected for pond discharge. The model was used to simulate the varying pond water level, the discharge flow and the resulting stream flow.

The five strategies tested were:

1. **Current standard**: The existing passive regulation based on the rating curve for the sliding valve (Passive control);
2. **Maximum utilisation of discharge permit**: A strategy of always discharging the maximum discharge allowed if possible (Active control);
3. **Maximum protection of stream:** A strategy always focusing on protecting the stream, and thus only discharging the flow rate equal to the available capacity in the stream before significant sediment transport is initiated (Active control);
4. **Active adaptive control:** A variation on strategy 3. However, this strategy allows the maximum permitted discharge to be discharged if the pond capacity is close to emergency discharge, thus ignoring the available capacity in the stream (Active control);
5. **Active predictive control:** A variation on strategy 4, but in this case, a rain "forecast" is implemented. Based on the forecast and present water level in the pond, the risk of emergency discharge is predicted. If there is a risk of emergency discharge, the pond is allowed to discharge at the maximum permitted rate (Active control).

Strategy 1 represents the existing strategy and serves as a reference for the other strategies. As the actual discharge is somewhat related to the water level, maximum discharge only occurs at maximum water level.

Strategy 2 is a situation in which the pond always discharges exactly what the permission allows. In a way, Strategy 2 simply follows the design criteria for the pond 100%.

Strategies 3-5 were designed to actively assess the available stream capacity. Strategy 3 only focused on keeping the streamflow below the stream capacity, without concerns for the capacity in the detention pond. The risk of such a strategy is that long periods of low available capacity in the stream will result in depleted capacity in the detention pond, and thus, overflow will occur.

A potential way of coping with this challenge could be to implement a “controlled increased outlet” when the water level comes near the maximum water level in order to avoid overflow; this was done in Strategy 4. The flow rate of this discharge could have been estimated based on several conditions; however, in this case, we chose to go no higher than the flow rate specified in the discharge permit.

Furthermore, we wanted to test whether taking into account predictions of the rain volume for the following two hours would improve the efficiency and protection of the discharge strategy. Thus, in the design of Strategy 5, a rain prediction was added to Strategy 4. Here, we also chose not to exceed the discharge permit. The forecast in the simulation is a “perfect nowcast” based on historical rain measurements. In reality, the quality of this forecast will be slightly worse than the assumption.

A range of different variations on control strategies could have been tested, but the four strategies selected represent different approaches to active control strategies.

CHAPTER 3. RESEARCH OUTCOMES

3.1. SCIENTIFIC OUTCOMES

In this section, the scientific outcome of the study is summarised, and the research questions are discussed and answered.

Which hydraulic characteristics do the outflow regulators exhibit during rain events?

- *Does there exist a consistent relationship between water level and discharge flow?*
- *To what degree do the hydraulics of the flow regulators represent the discharge permissions for the detention pond?*

In order to monitor the discharge from the detention ponds at the four experimental sites in Randers, Aarhus and Vejle, a method for translating the measured water level in the detention pond to a discharged flow rate was developed (described in **Paper I**). This method is based on a simple mass balance model to describe the pond system (in terms of inputs and outputs). After a rain event, the stormwater is detained in the detention pond, and after the inlet to the detention ponds has stopped, the only process in the pond is the discharge (under ideal conditions). Thus, any change in water level during dry weather must be caused by the discharge. If detailed knowledge about the pond geometry is available, then the water level can be translated into a surface area, and the decrease in water level can be translated into a decrease in volume. Hence this volume must be the discharged flow rate.

This method was tested at all four experimental sites, and the discharge for approximately the 15 largest discharge events during the monitoring period was calculated. The calculated discharge data was validated by the rating curve calculated flow data from the stream. The results from each pond fit almost the same curve when plotting the discharge against the water level. In this way, a rating curve for the pond discharge could be established, and the measured water level data translated into a discharged flow rate.

In **Paper III** the method was also conducted in a way establishing the full rating curve at once. Here it was possible to close the outlet from the detention pond, thus water could be detained until dry weather. Hereafter the outlet was opened, and the decreased water level could simply be translated into the discharge and a rating curve was established. However, this is not possible to do in all detention ponds, thus the other method would presumably be the most applicable.

In an ideal system, the inlet flow rate to the detention pond should be equal to the sum of the discharged flow rate and the positive volume accumulation in the detention pond. Knowledge about the water level and the discharged flow rate, based on the established rating curve, should therefore also make it possible to calculate the inlet to the detention pond. This would be desirable when calibrating a model of the urban sewer system. Furthermore, this opens for the possibility of detecting contributions from the drainage systems etc.

It is important to note that this method is highly dependent on accurate water level measurements – both when establishing the rating curve and translating it to the flow rate. The resolution of the OTT pressure sensor (OTT, 2019) used in this study was 1 mm, and for a logging frequency on 10 minutes this generate an uncertainty between 1.2 and 9.2 L/s ranging from the smallest detention pond to the largest during high flow conditions when establishing the rating curve. The reason for the varying uncertainty is, that the flow estimate calculated is dependent on the surface area, which again is dependent on the water level. Thus if the water level is uncertain, the flow estimate will be too. As a consequence, the accuracy of the water level measurements is very important. The accuracy can be increased by extending the time between logging the water level. This will be a trade-off as it also reduces the time resolution of the flow measurements.

When using water brakes as a regulation device, it is important to be aware that they usually come with a predefined rating curve from the producer. Rating curves for the two water brakes in the detention ponds were also available in this study. However, the data did not fit the predefined rating curves. The reason for this was the setup of the water brake in the discharge manhole – it was positioned differently than assumed by the producer. Therefore, in-situ measurements were necessary here.

Statistical analyses of the discharge data showed that the maximum permitted discharge flow rate was never discharged during the 2.5 years of monitoring. For all the ponds in this study, the results showed that the peak discharge measured reached a maximum of 75% of the permitted discharge flow rate. The statistical analyses also showed the difference between the number of rain events and the number of discharge events, thus providing knowledge about how often rain from rain events were accumulated in the detention pond. For the most efficient detention pond, 85% of the rain events were managed separately. A lower discharge permit would have resulted in a longer duration of the discharge, and thus a higher likelihood of accumulated stormwater in the pond.

In **Paper III**, an active control strategy which always discharges the maximum permitted flow rate if possible (Strategy 2, as described in Section 2.4) was compared to the existing passive flow regulation device installed in the pond which discharges to Polsterbæk (Strategy 1, as described in Section 2.4). A clear difference emerged between the two strategies. The result showed that passive regulation (Strategy 1) reduced the discharge from most rain events significantly more than required in the discharge permit. The interesting fact in this analysis was that the passive control (Strategy 1) also resulted in a higher peak flow during the overflow event simulated compared to Strategy 2, thus also result in a higher impact on the stream during overflow events.

The results from **Paper I** showed, that a consistent relation between the water level and discharge could be established. Thus, it was possible to make a low-cost flow monitoring system based on water level monitoring. This was required by potential end-users before they would adopt this approach about monitoring the discharge, and potentially implement an active control installation (see preface). An analysis of the results showed that a great deal of knowledge can be obtained about the dynamics in the detention ponds and flow regulation devices through monitoring – both the discharge and the discharged flow rate. The results also illustrate that the method developed is independent of the flow regulation device used in the pond, thus it can be used to monitor the discharge in all flow regulated detention ponds.

The method for calculating the discharge established in **Paper I** was used to adjust the discharge from the detention pond in Vejle in **Paper II and Paper III**.

How is stormwater discharge (increase of the flow) correlated with erosion/sediment transport in the stream?

- *Is a threshold value for sediment transport of different particle sizes a realistic measure of when sediment transport occurs?*
- *Can a detailed hydrodynamic stream model be used to predict the sediment transport which results from a discharged flow rate from a detention pond?*

Paper II focused on establishing a correlation between the sediment transport and discharged flow rate. Here, measurements of bed sediment transport were taken at two measurement stations downstream from the point of discharge in Polsterbæk, in order to determine whether local variations were evident within a short distance.

The suspended transport was measured in just one station. These results showed that relatively small changes in the stream flow resulted in a large increase in the transport of suspended sediment. Furthermore, discharging step-wise more water from the pond, resulting in a cautious, step-by-step increase in streamflow, did not result in an increased transport of suspended sediment. This could indicate that the supply is the limiting factor for suspended sediment transport in Polsterbæk.

The experiment showed significant local variation between amounts of bed sediment transport within a short distance. This is likely due to the differences in bed sediment composition. In the most representative measurement station, the sediment transport increased gradually until the streamflow was around 50 L/s, but even though the discharge was increased to around 60 L/s, the sediment transport decreased. This indicates a supply limit was also a dominant factor in regards of bed sediment to be transported. In the other measurement station, a different reaction pattern was detected. Here, the peak in sediment transport occurred after the peak in discharge, and thus the peak in streamflow. These unexpected dynamics measured in here are assumed to be due to a sand deposition situated upstream from this measurement station. The bed sediment transport measurements showed that indications of a threshold appeared, when the streamflow reached 28 L/s. It was not possible to draw this conclusion based of the mass of sediment transport, however the median size of the sediment transported increased significantly when changing the streamflow from 20 L/s to 28 L/s. The transported median particle diameter was approximately the same for all streamflows above the threshold in the measurement station without the sand deposition.

In order to test which traditional threshold model was the most accurate for determining the threshold of sediment transport for a small stream like Polsterbæk, we tested 11 different threshold formulas based on the collected particle sizes. These included five formulas for critical shear stress and six formulas for critical stream power. This analysis revealed that none of the formulas fit the measured results (**Paper II**). Based on the translation of the calculated values for the shear stress and stream power to the particle size predicted to move using the 11 formulas, particles of 5 - 60 times the 95th percentile should have moved. Thus, great care should be taken before threshold models are used for evaluating the impacts of stormwater detention ponds. On the other hand, the models might be more suited to larger lowland streams with a different substrate composition.

The explanation for this lack of conformity could be that most theories about sediment transport are based on flume experiments, according to Rickenmann and McArdell (2007). Comparing these results to other in-situ experiments, it appeared that the prediction of sediment transport in small streams is generally difficult. Clarck and Wynn (2009), for instance, experienced similar discrepancies. An explanation supported by Petit et al. (2005) is that a lot of potential energy which could be used for sediment transport, is lost in order to overcome the form roughness and bed form resistance. Their results indicated that in small streams, less than 30% of the resulting shear stress is available for sediment transport. This is also supported by Fischenich (2001), who states that the mixing of the stream bed with large particles shielding the small particles can have an impact of almost an order of magnitude.

Thus, the conclusion is that in a small stream with a very mixed bed composition and / or relatively high form roughness like Polsterbæk, in-situ measurements of the sediment transport are necessary in order to define the threshold of sediment movement. When defining the threshold of sediment transport, it is important to remember that sediment transport is not equal to erosion. Sediment transport is a natural process in the stream; what possibly could be negative is *excess* sediment transport, above the natural range. Thus, a detailed knowledge about the baseflow sediment transport and the bed composition is necessary to evaluate the consequence of sediment transport.

In order to determine whether the effects of a pond discharge were just local in the upstream part of the stream, sediment transport (both suspended and bed sediment transport) was measured at four measurement stations within 700 meters of the stream – 200 meters apart. The results from those measurements showed no indication that the sediment transport was local close to the point of discharge. In fact, the highest sediment transport was measured at the station furthest downstream from the point of discharge (700 m), both in terms of suspended sediment transport and bed sediment transport. These measurements were supported by hydraulic stream models created in MIKE 11, which showed that the maximum shear stress would appear at the section of the stream between 500 and 700 meters downstream from the point of discharge. Hence this would be the place to test the capacity, if more experiments were to be conducted in Polsterbæk. Moreover, if the discharge should be controlled permanently in Polsterbæk, a permanent measurement station would be probably be established here.

A traditional approach to evaluating discharge from a detention pond would be to set up a dynamic stream model and evaluate different discharges. This was also done in **Paper III**, and the results were calibrated based on water level measurements in the four measurements stations mentioned above. The results from this work show that the steep slope and the bed composition consistent large stones in a combination with low baseflow conditions made the hydraulics of the stream resemble a series of pools overflowing to downstream pools (See stream during different conditions in Figure 3.1). The assumptions of the dynamic stream model MIKE 11 did not correspond to this situation. However, at higher flow rates, the model performed much better. This could indicate that the modelling approach is more viable for lowland streams with a gentle slope, where the energy loss originates from friction. The results are therefore not conclusive regarding a modelling approach, as Polsterbæk is not representative and differs greatly from the assumptions usually implemented in stream models. This again implies the difficulties in predicting the effects of the discharge in small streams with relatively large form resistance.

Figure 3.1: *Illustration of Polsterbæk in three different flow situations going from dry weather flow, medium-sized flow and high flow.*

Thus, a correlation between sediment transport and discharge could be established. However, the traditional threshold models for critical shear stress and critical stream power do not apply to all streams. In principle, the threshold of different particle sizes should be a good measure for the prediction of increased sediment transport or erosion. It requires a detailed knowledge of the bed sediment composition, the energy loss, and sediment sources. Predicting sediment transport during low flow conditions in a stream like Polsterbæk was problematic, but during high flow conditions, the results of the dynamic MIKE 11 model correlated well with the measurements. However, in streams where such threshold models cannot be applied, measurements will still be necessary.

Can information about the here-and-now stream capacity of the receiving stream improve the discharge strategy?

- *Is it possible to minimise the negative effect of stormwater discharge by controlling the discharge based on the actual stream capacity?*
- *Would the implementation of storm forecasts improve the efficiency of a control strategy solution and result in fewer emergency overflow events?*

In **Paper III**, five different discharge strategies, were tested using a volume balance model. The purpose of the simulations was to make a systematic comparison of the strategies and conclude which did the best job in balancing the respect of the stream capacity and achieving the best pond efficiency.

The five strategies tested are described in Section 2.4 and have the following foci:

1. Current strategy of passive control
2. Maximum utilisation of the discharge permit
3. Maximum protection of the stream
4. Active adaptive control
5. Active predictive control

The comparison of the model results did not give a clear result of which strategy was the best.

Strategy 2 gave the smallest peak flow and the shortest duration of overflow. However, it was the one which exceeded the stream capacity for the longest period.

Strategy 3 gave the absolute highest peak flow during overflow and the largest number and duration of overflows. However, it respected the stream capacity 20% more of the time than Strategy 2.

Strategies 4 and 5 were almost equal to strategy 3 in terms of respecting the stream capacity. Strategy 5 in particular, significantly reduced the overflow compared to Strategy 3. However, even though the overflow was reduced, the peak flow was still approximately 60% higher than the result of Strategy 2.

Compared to the existing discharge strategy, Strategy 1, Strategy 2 exceeded the stream capacity 10% more frequently, and Strategy 5 10% less frequently. The peak flow discharge was approximately the same in Strategy 1 and 5, but Strategy 2 reduced it by 60%.

Thus, whether Strategy 2 or 5 performs the best depends entirely on which effect is the most critical in the stream. Whether maximum everyday protection or protection during overflow situations is the most important must be dependent on the stream.

In this case, it must be noted that the capacity was defined based on the maximum flow before the occurrence of transport of a significantly increased median particle size, and that this flow rate was exceeded by the "unaffected" streamflow several times during the monitoring period. Sediment transport is a natural process; thus, in order to design a control strategy which is possible to implement in the detention pond, it would be beneficial to define what constitutes "excess sediment transport" compared to the natural variation.

The largest change compared to the traditional approach is that three of the control strategies tested are based on actual measurements of the effects in the stream as the primary focus. Most control strategies previously tested in detention ponds have been based on either optimising the sewer system or providing optimal protection of the stream by trying to keep the discharge as low as possible, thus assuming that the capacity in the stream is always limited (further described in **Paper III**).

In this test, the resulting flow in the stream was measured and the discharge was adapted based on this. Thus, the varying capacity determines the discharge pattern by utilising the available stream capacity if it is high, and reducing the discharge when the available capacity is low. The results showed that it was possible to minimise the negative effects of the existing stormwater discharge from the detention pond in the stream by controlling the pond discharge based on the here-and-now available capacity in the stream, especially if implementing a strategy of predictive control.

3.2. COMMERCIAL OUTCOMES

This work is the result of an industrial Ph.D study, where both scientific results and commercial outcomes are important. The commercial outcomes are related to the benefits for society, water utility companies, and the consulting engineering company Orbicon|WSP.

This project aimed to develop a new concept, offering multifaceted solutions to the challenges of making room for stormwater management in the city. The special feature of this project is that stream systems and urban drainage systems are considered as *one* system. Thus, management of the discharge from the urban drainage system is based on the capacity and the robustness of the specific stream which receives the water. This strategy makes it possible to discharge the water both more efficiently and with respect for the stream capacity. Timing the stormwater discharge correctly according to the varying streamflow, a larger volume of stormwater can be discharged without it increasing the hydraulic load in the receiving stream or damaging the stream ecology. Although not tested in this work, the whole stream and all the stormwater detention ponds should be evaluated as one system.

Overall, the purpose of the new concept was to help:

- to assure better stream quality despite the ongoing urbanisation;
- to decrease the need for space for urban water management;
- to consider streams and stormwater systems as *one* system, which opens for:
    - Assessing the capacity in the stream actively in the stormwater management
    - The possibility that improved conditions in the stream can be used as an active tool in the stormwater management

Reducing the necessary volume of the detention ponds, and thus also the need for space for stormwater management, is economically beneficial to water utility companies as well as to industries with their own stormwater management. This applies to both establishing costs and maintenance. Thus, this was a focus point in the project start-up. Another initiating point for the project was to focus on the capacity of and the conditions in the streams, and use this as the focus point when issuing a specific discharge permit, rather than adopting standard requirements of e.g. 1 L/s/ha, or a 2-year maximum area-specific runoff measured at a random position in the stream.

This could be characterised as a “win-win” solution, where both the storm drainage system and the receiving streams could benefit from the solutions developed.

Climate changes and urbanisation make the task of more efficient water management even more important, and the results from this study will be able to support the development of how to handle everyday rain events more efficiently and environmental sustainable. Thus, more of the budget of the water utility companies will be available for climate adaptation and renewal, thereby improving the efficiency of the sewer systems and wastewater treatment plants.

3.2.1. COMMERCIAL OUTCOMES IN RELATION TO PAPER I:

Based on the measurements in the four experimental sites, a method for translating water level measurements in a detention pond to a discharge flow rate was developed. Today, there are very rarely any requirements about monitoring in detention ponds when a discharge permit is issued; thus, it is not examined whether the final design complies with the permit. The method developed makes it easy and cheap to monitor the discharge from the detention pond. This makes monitoring a more accessible investment for the water utility companies, since a small investment like a water level station provides them with a lot of knowledge. The gains from monitoring the discharge are that more knowledge about the processes in different types of detention ponds can be collected and used in future projects. Furthermore, the water utility companies can document the discharge, and thus the impact on the stream, in the case of problems with flooding or similar problems downstream from the point of discharge. This will be beneficial knowledge for both the water utility companies and the municipalities.

Monitoring also opens up for more detailed statistical analyses of the utility of the pond capacity. The statistical analyses made in relation to **Paper I** of a detention pond with a water brake as regulator showed that for 90% of the time discharging from a detention pond, less than 10% of the permitted discharge flow rate was discharged, and for 75% of the time, less than 20% was discharged. This was actually surprising to most of the municipalities and water utility companies following the project. More detailed knowledge about the dynamics of the different regulation devices makes it easier to predict the effect of the requirements issued in the discharge permits. More analyses like these would open for a more nuanced debate about the size of the discharge permit. As a result of this project, some water utility companies are considering monitoring the water level in their detention ponds.

Besides the potential in monitoring the discharge, many water utility companies also see a potential in water level monitoring in order to ensure the cost-efficient maintenance of the detention ponds – if the water level is still high during a dry weather period, the outlet might be clogged. This enables the water utility company to remove the clogging material before a damaging overflow event occurs, thereby avoiding costly damages to stormwater pond facilities as well as the urban surroundings and the stream environment. Monitoring of the water level will also help to gain a better understanding of the system. Some of the analyses in **Paper I** showed an example of a delayed peak in the water level after a rain event. This was caused by discharge from a drainage system which the water company did not know was connected to the urban drainage system.

Furthermore, it was also shown in **Paper I** that water level monitoring could be used to determine the *inlet* to the detention pond. Such measurements provide many perspectives in relation to the calibration and validation of urban stormwater models. Detailed measurements of both the rain intensity and the inlet to the detention ponds would also make it possible to study the effect of runoff from urban pervious areas on a large scale, complementing studies by Nielsen (2019).

3.2.2. COMMERCIAL OUTCOMES IN RELATION TO PAPER II:

The results from the sediment transport experiments showed that traditional threshold models for predicting the movement of sediment particles did not match the measured sediment transport. Hence it is not possible to make pure model predictions of the effect of a given discharge flow rate – especially not in small heterogeneous streams with a high slope. This is very important knowledge for both the local authorities and the water utility companies administrating the discharge permits and analysing the effects of potential maximum flow rates. Estimations of potential effects in the streams require in-situ measurements and analysis of the bed composition and the limiting factors for sediment transport. In the stream Polsterbæk, the sediment transport measured was not problematic, because most of the sediment transported is expected to be over-bank-sediment led to the steam during larger rain events. In order to reach this conclusion, however, a system analysis is essential. In relation to this, more data should be collected from other types of streams in order to be able to design generally applicable methods. The equipment and methods developed for the experiments in **Paper II** and **Paper III** would be useful in case more measurements need to be done. Because knowledge about sediment transport and erosion influences the stormwater management practices, water utility companies will have a financial incentive to contribute to obtaining this knowledge.

Knowledge about the critical conditions and vulnerable sections of the stream also makes it possible to possible to point out the problems in the stream. This can be used actively when issuing a discharge permit. Instead of just reducing the discharge, the water utility companies could restore the stream at the problematic sections, thus increasing its capacity and increasing the accepted flow rate in the discharge permit. As a side effect, this will improve the stream's resilience against extreme flow events.

3.2.3. COMMERCIAL OUTCOMES IN RELATION TO PAPER III:

First, the sediment transport measurements in **Paper III** support the results from **Paper II**, that the potential for sediment transport / erosion has to be measured. The results show that sediment transport as a result of discharging not only occurs just downstream from the point of discharge, but in this case primarily 700 meters further downstream from the point of discharge. This indicates that it is essential to make a system analysis before permitting a specific discharge flow rate.

Paper III also presents the possibilities of designing a controlled discharge strategy in order to minimise sediment transport, and thus the ecological impact on the stream. Controlling the discharge from a detention pond has a large commercial potential. The innovation is that sensors in the stream continuously measure and calculate the available capacity in the stream – without causing additional sediment transport.

It was not possible to draw a clear conclusion about which strategy performed the best; the strategy which most often utilised the discharge permit fully, or the strategy which focused on protecting the available here-and-now capacity but accepted an increased discharge in the case of predicted pond capacity depletion? The predictive strategy did improve the conditions compared to the existing strategy, which must be considered a success. Furthermore, the fact that it opens for a more nuanced discussion, of whether the stream should be maximally protected in an everyday situation or in an overflow situation, is a significant improvement on the existing process.

Also, it is expected that tests in another experimental site would give clearer results. Here, it was not possible to define the limit for excess sediment transport, so the limit for measured increased particle size was used as a guideline. This made for a large difference between the design criteria and the accepted discharge very wide, thus leaving limited room for a different utilisation of the pond volume. This shows that it might not be possible to make a control strategy which fits all situations. Even in this case, an improvement compared to the existing strategy was obtained, even if it was only on one parameter.

This opens up for the possibility of installing equal control structures in other stormwater detention ponds and optimising the utility of those. Controlled discharge can thus both be used in existing detention ponds in case more water is let into it, or in the case of new detention ponds being established in places with limited space available. It also opens up for the possibility of making existing detention ponds less problematic for the recipient streams – without making the detention ponds larger.

This approach makes it possible to develop and offer more adaptive control systems to water utility companies, and they can then discuss with the municipality which control strategy is the most relevant for a particular stream and detention pond.

When the potential of controlled discharges was presented to the collaborating water utility companies in the project (see preface), they pointed out the difficulties in installing control structures if they were dependent on a fixed power supply from the public power service. They suspected that the savings of the smaller volume would be offset by the costs of connecting to the main power supply – especially in remote areas. In order to investigate this, funding from VUDP (Programme for the Development and Demonstration of Technology in the Danish Water Sector) was applied for and awarded. The VUDP-funded project “ReLeVand” (Danish: *Regulerbar LavEnergi Vandbremsen*, “Adjustable Dynamic Low-Energy Water Brake” or ADYLE-Brake in English) aims to develop an agile, cost-effective and sustainable environmental technology to control the discharge from detention ponds. The project is a collaboration between the water brake producing company Mosbaek A/S, Aalborg University, Orbicon|WSP and the water utility company Favrskov Forsyning. The reason why the control device is based on a water brake is that this is the most commonly used regulation device for discharges in Denmark. Thus, the aim is to develop a “plug-and-play” device with the same dimensions as the existing water brakes. The motor supplying the control structure runs on solar energy.

Through this study, Orbicon|WSP has obtained a number of insights and methods which can be used for present and future projects. The potential in offering water companies better and more resilient solutions are significant. The commercial gain of this research has already been seen in a number of projects, for instance during projects where the varying capacity and knowledge about sediment disturbance has been assessed actively. Furthermore, the knowledge about stream capacity has been used to plan a stream restoration for water utility companies in order to avoid the standard relatively restrictive discharge permit. Additionally, Vejle Spildevand has utilised the knowledge gained during the project. They are now testing a different type of passive control focusing on simulating the “natural” runoff.

CHAPTER 4. CONCLUSIONS

The research hypothesis to this study was:

> *It is possible to switch from the present maximum discharge permission methodology to a flexible approach where the actual here-and-now stream capacity determines the discharge from the stormwater detention pond. This could be done in such a way that it benefits both the stream and the operation of the pond.*

This hypothesis was proven to be true, based on the answer for the initiating questions.

I. How do we get simple, cost-effective and reliable measurements of the *actual* discharge from stormwater detention ponds?

In order to develop a cost-effective, simple and reliable method to monitor the discharge, a water level gauge was set up in four ponds. Based on detailed knowledge about the pond geometry, the change in water level during ideal conditions (no inflow, infiltration, leak or precipitation), can be translated to a discharged flow rate. Based on the decreasing water level from several rain events, rating curves were established for all four ponds. When the rating curve is established, this defines the fixed relation between the pond water level and discharge.

II. How do we evaluate the impact of the discharge on the stream?

The experiments conducted in Polsterbæk showed that discharge from stormwater detention ponds influences the water level in the stream and potentially does have an effect on the sediment transport in the stream. A threshold of sediment transport could be identified based on the experiments. However, the traditional threshold models for sediment transport did not apply to the results from Polsterbæk, which is a small high slope stream with a highly heterogeneous bed sediment composition and high form roughness. Here, it must be noted that sediment transport is a natural process, and it is not necessarily damaging for the stream. The parameter which must be assessed is the excess sediment transport compared to the natural situation.

III. Which approach to control of the discharge could improve the existing operation of stormwater detention ponds?

The prevailing approach to flow regulation in stormwater detention ponds is to issue a discharge permit with a fixed maximum discharge allowed, and a great deal of effort is put into determining the size of the maximum discharge. The primary method of flow regulation currently used is passive regulation devices, such as water brakes or throttling pipes, which discharge the highest flow rate when the pond is full. This practise does not actively asses the stream capacity, especially not the here-and-now available capacity. The risk is that, in order avoid high discharges during high flow conditions in the stream, the maximum discharge permitted will be very restrictive. The most practical method to control the stream capacity is to implement a method of active discharge control. In such a case, a higher discharge rate can be accepted during low flow conditions, when the available capacity is high; and water can be detained during high flow conditions, when the available capacity is either low or depleted. In this way, it is possible to utilise the capacity in both the receiving stream and the detention pond.

CHAPTER 5. FUTURE PERSPECTIVES

In this study, experiments with sediment transport have been conducted in the stream Polsterbæk, which was an ideal place because the streamflow could be dictated almost solely by the discharge from the detention pond during dry weather conditions. However, the stream is not generally representative of Danish streams due to its high slope and heterogeneous sediment composition. Thus, results from this stream cannot be generalised to other Danish streams. Therefore, more studies similar to the experiments in Polsterbæk should be conducted in other types of streams in order to obtain better knowledge about the sediment dynamics in general. Since the risk of erosion and the work of meeting the criteria for good ecological conditions in the streams is a great concern of the present time, this should be an analysis of great interest the authorities as well as the water utility companies.

In this context, it must be noted that the measurements in this study showed a threshold for sediment transport. However, sediment transport is a natural process, and the stream itself exceeded the threshold on a regular basis. In order to asses the critical factor regarding sediment transport, further studies about the difference between the threshold of sediment transport and the threshold of erosion must be conducted. In a stream where the resulting streamflow is highly dependent on the pond discharge, like in Polsterbæk, avoiding sediment transport might actually damage the stream, because sedimentation has also been proven to have a negative impact on the stream ecology. Thus, the ideal scenario must be for the discharge to ensure frequent sediment transport for small sedimented particles during low flow conditions, but not result in erosion which changes the stream geometry. More knowledge about the natural sediment transport variation should be gained.

A welcome side effect of having knowledge about the sediment transport in different types of streams is that it is possible to identify the critical section of the streams. These are the sections that should dictate the discharge accepted in the discharge permits for the detention ponds. This knowledge about where the streams are vulnerable might also help us to determine why they have become so. An insight into this would help us develop methods to make the streams more robust. Thus, stream restoration could be a useful tool when issuing discharge permits. When discharging to a vulnerable stream with poor ecological conditions, the discharge must either be reduced significantly, or the conditions in the sections of the stream which dictate the reduced discharge must be improved, thus leading to a more lenient discharge requirement.

The focus in this study has been to observe the discharge from *one* detention pond to a stream, and to control the discharge from this detention pond based on the capacity and varying flow in the stream. However, often a stream receives discharge from several detention ponds, and therefore, those should be taken into consideration too, in order to gain the maximum positive effect of the control strategy. Hence it is necessary to identify all vulnerable sections of the stream and control the sum of all discharges based on the combined effect – both upstream and downstream from each point of discharge. This will require a denser network of stream measurement gauges, such that the here-and-now effect in the stream is always known, making it possible to act based on this. This will probably require a network of IoT devises in the stream in order for the gauges to be online at all times.

When controlling the discharge from the detention ponds, the hydraulic conditions might not always be the most critical in terms of the resulting impact on the stream. If a regulator is installed, this opens up for the possibility to include a variety of parameters in the control strategy. During this study, the parameters of the greatest concern have been temperature, oxygen concentration and pH. During the summer months, the temperature in the permanent volume in the monitored detention ponds reached just below 30ºC. A discharge of this temperature to a low flow stream might have a very negative effect on the stream ecology. A control strategy could manage this problem by detaining the stormwater during such conditions and control the discharge based on causing the minimum temperature impact – e.g. by discharging during the night. Such a practice, however, also requires considerations of the effects on oxygen, due to the decreased oxygen concentrations during the night. Control based on more parameters requires detailed knowledge about the processes in both the streams and the detention ponds, which might prevent the implementation of such a strategy. However, actively considering these kinds of effects will lead to more detailed knowledge about how the urban discharges affect the streams, and whether the effects are significant.

A simpler way to actively asses the stream capacity without the implementation of an active control system could be to make a seasonally varying discharge permit. In many streams affected by weeds, sediment transport is often not problematic during summertime, while it could be during the wintertime, when the bed and banks are exposed and the runoff from the stream catchment is higher. Conversely, the opposite situation could apply for the risk of flooding.

A further perspective in assessing the stream capacity is to actually measure the parameters which are important for the ecology. Sediment transport or erosion, temperature, oxygen concentration, pH, etc. are indirect measures of the conditions affecting the plants, fish and invertebrates. In order to actively improve their conditions, frequent measurements of the quality of those parameters could be an improvement.

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APPENDICES

This PhD-thesis consists of a collection of three scientific papers. The papers can be found in appendix A, B, and C as listed below.

Apendix A – Paper I: Thomsen, A. T. H., Nielsen, J. E., Rasmussen, M. R. (2020). A simplified method for measuring the discharge from stormwater detention ponds. (Submitted to Journal of Environmental Management)

Apendix B – Paper II: Thomsen, A. T. H., Nielsen, J. E., Riis, T., Rasmussen, M. R. (2020). Hydraulic effects of stormwater discharge into a small stream (Submitted to Journal of Environmental Management)

Apendix C – Paper III: Thomsen, A. T. H., Nielsen, J. E., Sørensen, L., Claes, N., Rasmussen, M. R. (2020). Using the stream capacity as a parameter in controlling the discharge from stormwater detention ponds (submitted to Journal of Hydrology)

Appendix A. Paper I - A simplified method for measuring the discharge from stormwater detention ponds

Appendix B. Paper II - Hydraulic effects of stormwater discharge into a small stream

Appendix C. Paper III - Using the stream capacity as a parameter in controlling the discharge from stormwater detention ponds

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